CONVERGENCE OF THE NMMB/BSC-CTM MODEL IN THE CALIOPE SYSTEM

PHASE II: METEOROLOGICAL VALUATION

BSC-AC-2015-002

NMMB/BSC-CTM, CALIOPE, evaluation, WRF

Lorenzo Fileni, Sara Basart, María Teresa Pay

Earth Sciences Department

Barcelona Supercomputing Center - Centro Nacional de Supercomputación (BSC-CNS)

04 September 2015

Series: Earth Sciences (ES) Technical Report

A full list of ES Publications can be found on our website under:

https://earth.bsc.es/wiki/doku.php?id=library:external:technical_memoranda

Summary

The Earth Sciences Department of the Barcelona Supercomputing Center (ES-BSC; http://www.bsc.es/earth-sciences) provides daily operational weather forecasts for European and regional domains by means of the WRFv3.5.1 model implemented in the CALIOPE air quality forecasting system (AQFS). The WRFv3.5.1 model provides the meteorological forecast to the CALIOPE system and the NMMB/BSC model is the meteorological module of the Chemical Transport model NMMB-BSC-CTM.

The present analysis aims to evaluate the performance of the WRF-ARW v3.3.1 model at two different resolutions and NMMB/BSC over the European domain. For the evaluation, we used observations from 371 stations belonging to the METAR network. The simulated data consists in diagnostic simulations of the WRF v3.3.1 model at 25km and 0.44º of resolution respectively, and NMMB/BSC model at 25km. The modelled meteorological parameters consist of 365 daily runs in 24-hour daily forecasts for the WRF at 25-km and 3-hour for the WRF at 0.44º. The approach to the models evaluation consists in a comparison between models output and measured data set also using 3 statistical parameters.

This study identified a better model-observation matching of the WRFv3.3.1 at 25 km of resolution against the simulation with 0.44º of resolution. Some slight discrepancies between the two model simulations arise in the temperature and wind speed variables, involving mainly MB (mean bias) and RMSE (root mean square error) during cold months, although both approximate very well the observations. The wind direction analysis highlights a predisposition of the model to simulate wind directions vectors mainly from west over the Atlantic regions and central Europe and mainly from east over the eastern European countries. The directions error is stronger over the south of Europe with a tendency to decrease moving northward.

Finally, the analysis of the statistical parameters assess that the model performances are sensible at complex terrains and they improve when the altitude decreases. The evaluation of this WRFv3.3.1 version with two different spatial resolutions, has allowed understanding that it shows better abilities over central and north Europe as well as in some Atlantic coasts where the flat and smooth topography is predominant. The Mediterranean and Balkans countries, with complex terrains are areas where most relevant discrepancies in model-observation matching occur.

Contents

1. Objectives

In the present report we performed a models comparison of two meteorological models such as WRF v3.3.1 and NMMB against ground-based observations from METAR network stations over Europe. The main objective is to analyze the differences and the performances of both models in reproducing meteorological variables levels and distribution over Europe with the final purpose of assessing which is the more adequate model within the CALIOPE system. This task will support the replacement of WRF model by NMMB within the CALIOPE air Quality Forecasting System.

2. Methodology

2.1 Model system configuration

In the present work, we used the WRF and NMMB models for providing meteorological variables such as Ambient Temperature at 2 meters, Wind Speed and Wind Direction at 10 meters (hereafter "T2", "WS10" and "WD10" respectively). The WRF simulation performed by the BSC for TFMM (Task Force on Measurement and Modelling) at 25-km resolution over Europe has the same set-up as the Euro-Cordex climate downscaling program that performed the simulation with 0.44° of resolution (https://wiki.met.no/emep/emep-experts/tfmmtrendeurodelta). The simulated variables distributions and values consist of 24-hour daily forecasts, whit 3-hourly time resolution for the WRF at 0.44° and 1-h in time resolution for WRF 25km, over a period of 365 days in the whole year 2010. The initial conditions in the models are defined by the 24-hour forecast from the previous-day model run. The **Table 1** shows the WRF-ARW and NMMB model configurations.

Table 1: Models configurations

Model configuration	*WRF v3.3.1*	*WRF v3.3.1*
IC - BC	ERA-Interim global reanalysis (resolution ~80 km)	
Coordinate system	latitude and longitude (including global)	Lambert Conformal
Horizontal setting	0.44° x 0.44° (WEST-EAST_GRID_DIMENSION=120 SOUTH-NORTH_GRID_DIMENSION=117)	25 km x 25 km (WEST-EAST_GRID_DIMENSION=176) SOUTH-NORTH_GRID_DIMENSION=197)
Vertical setting	31 layers	
Microphysics	Morrison 2-mom - Morrison, Thompson and Tatarskii (2009, MWR)	
LW,RW radiation	RRTMG - Iacono et al. (2008, JGR)	
Cumulus scheme	Tiedtke -Tiedtke 1989, MWR, Zhang et al. (2011, MWR)	
Boundary layer	MYNN2 - Nakanishi and Niino (2006, BLM)	
Surface layer	Nakanishi and Niino	

2.2 Ground-based meteorological station observations

The values and the spatial distribution of the meteorological variables simulated by the models are compared against observations extracted from the METeorological Aerodrome Report (hereafter "METAR") network database (http://rda.ucar.edu/). This is a global network of stations that make available hourly surface observations of meteorological variable providing a long-term amount of data. For the models evaluation have been selected 371 stations Europe-wide distributed with a temporal data coverage ≥ 85% of 2010, well distributed throughout the year and coinciding with the model outputs (see

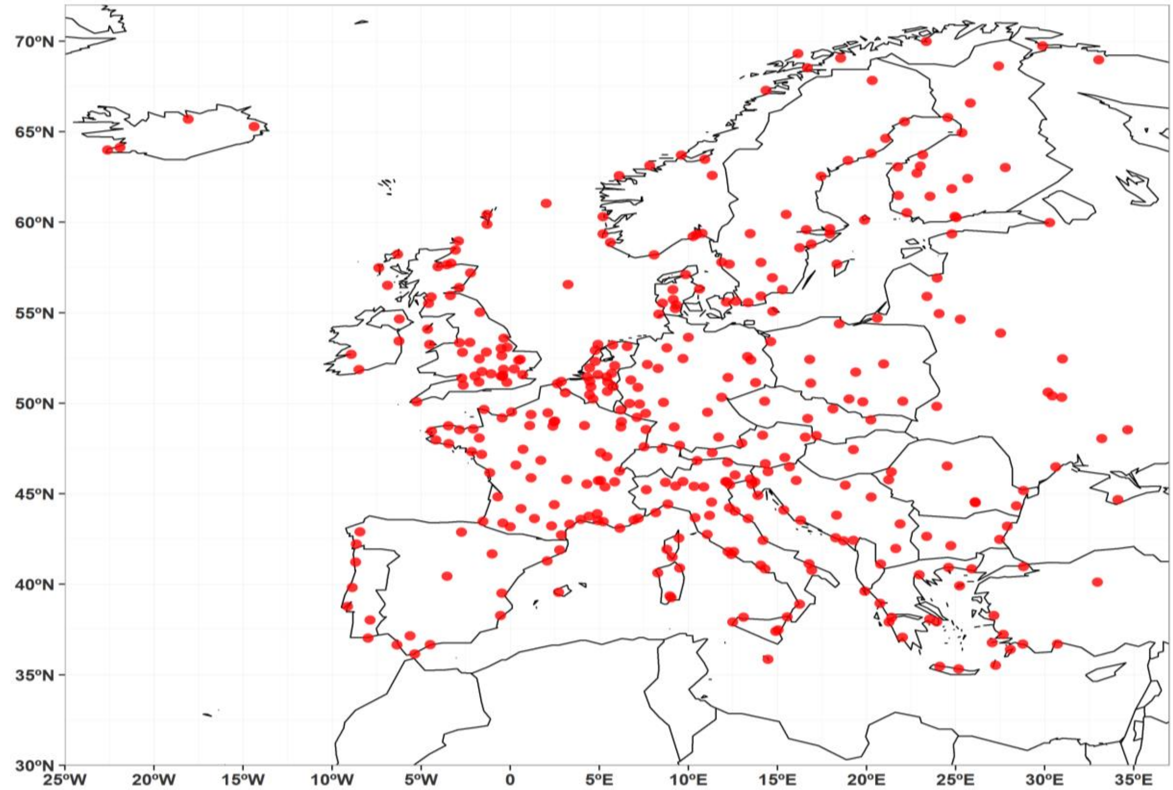


Figure 1). They provided hourly averaged T2, WD10 and WS10 values, for the year 2010. The considered domain fall within the following coordinates: latitude between 70ºN – 35ºN and longitude between 35ºE and 25ºW. Finally, because some observations data set contained non-sense values they were not considered. The exclusions have been done according to the following criteria:

- T2 < 220 Kº (-53º) and T2 > 325 Kº (52º)
- WS10 > 50 m/s (180 km/h)
- WD10 > 360º

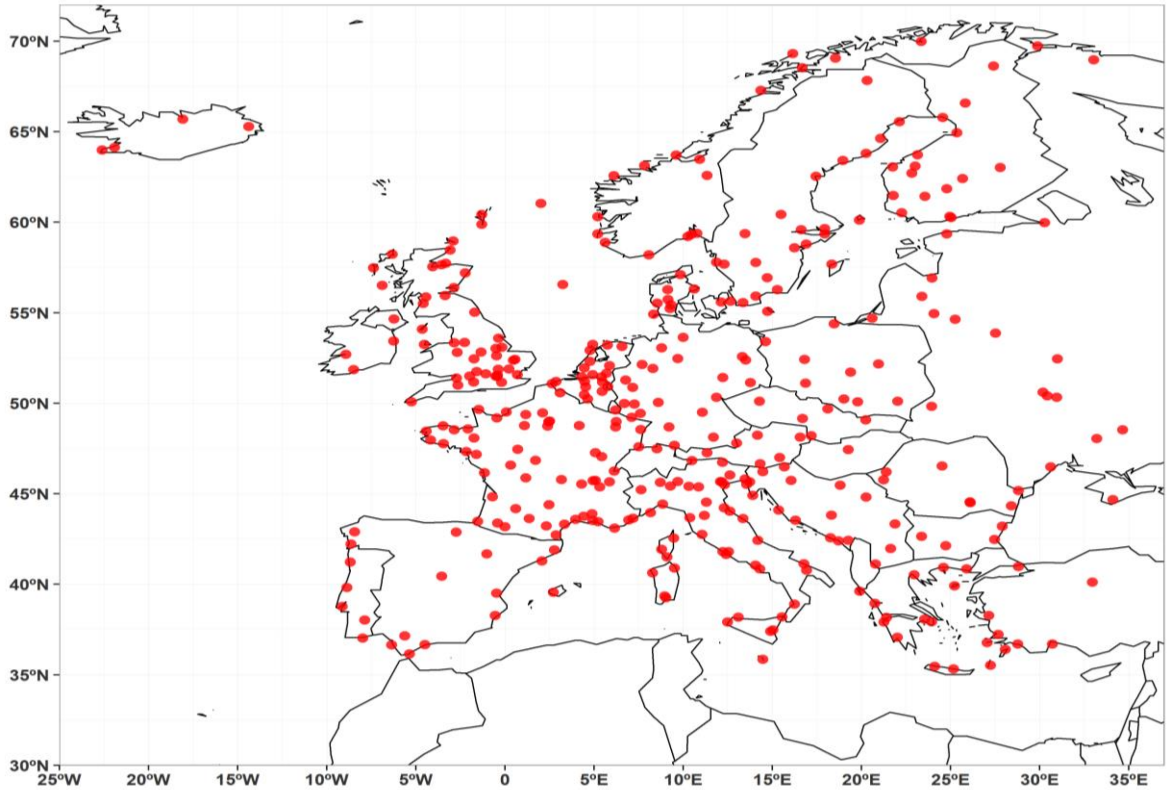


Figure 1 . Position of the 371 selected METAR stations

2.3 Evaluation method

We used a set of discrete statistics parameters such as correlation coefficient (r), mean bias (MB) and root mean square error (RMSE) to assess the models output against ground-based observations. These parameters have been study and represented in terms of spatial and temporal distribution in order to evaluate relationships with geographical position and topography.

In addition, the model skills were also investigated per different ranges of temperature and wind speed, in order to highlight strong points and/or shortcomings of the model depending on different intervals of values.

These statistics parameters have been also analyzed in respect to the altitude of all the ground-based stations. They were divided into 4 classes of altitude in order to assess the sensibility of the models in respect to altitudes variations. These classes were identified according to the 50^{th}, 75^{th} and 95^{th} percentile of the total altitude values (see **Figure 2**):

- 186 stations located below 60 m (50^{th} percentile)
- 94 stations located between 61 m and 155 m (75^{th} percentile)
- 72 stations located between 156 m and 430 m (95^{th} percentile)
- 19 stations located between 431 m and 1800 m (last 5% of the altitude values)

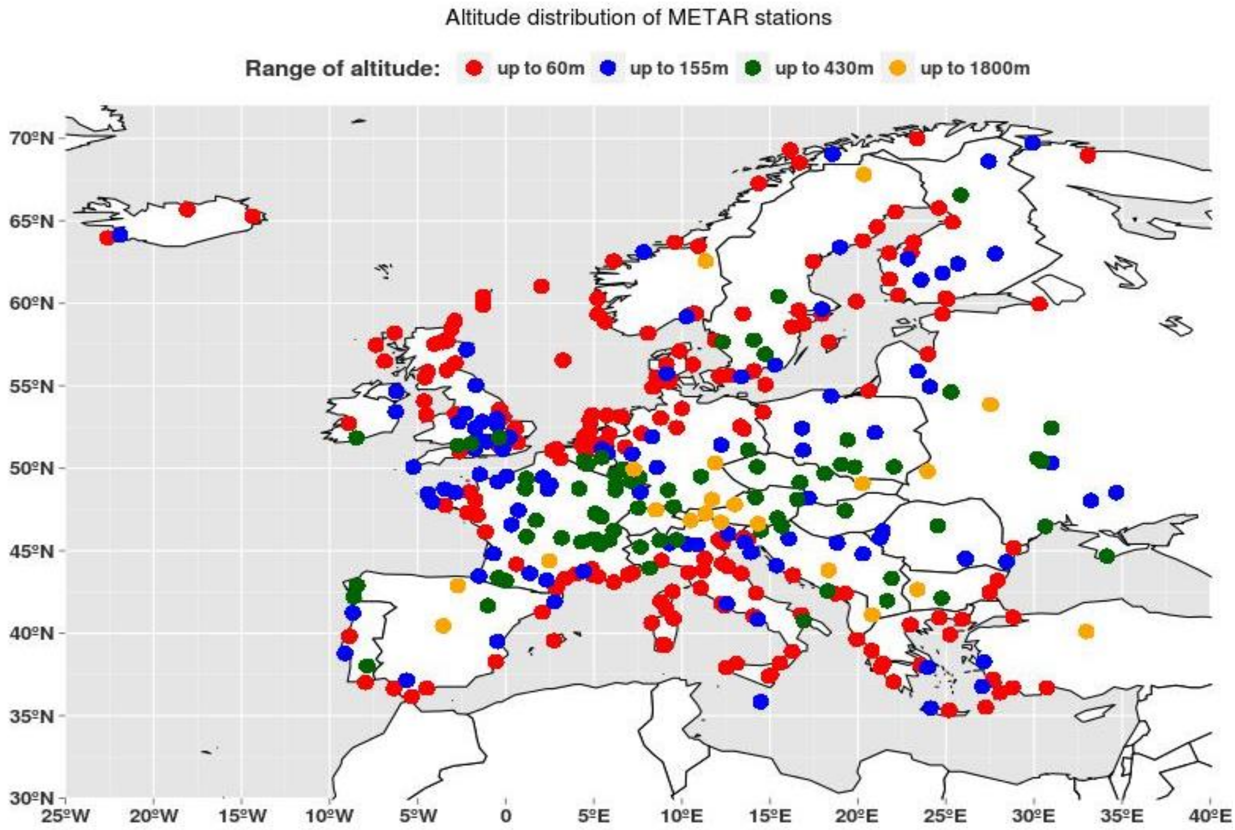


Figure 2. METAR stations classified per altitude

Finally, have been selected 8 METAR stations to carry on a local model evaluation in order to study and understand in detail eventual problems occurred during the global analysis. The stations were grouped in 4 zones: 2 in the Mediterranean area, 2 in the flat regions of continental Europe, 2 along the Atlantic coasts of the domain and lastly 2 stations over two different complex topography regions. The stations have been chosen with the purpose of analyzing different areas where the model has problems in reproducing accurately the local meteorological conditions (see **Table 2** and **Figure 3**).

Table 2. Details of the selected ground-based meteorological stations

SITE NAME	ZONE	SITE ID	LATITUDE (°)	LONGITUDE (°)	ALTITUDE (m)
Cagliari (I)	Mediterranean coasts	LIEE	39.25	9.05	18
Dalaman (TR)	Mediterranean coasts	LTBS	36.70	28.78	2
Hamburg (D)	Flat continental-EU	EDDH	53.63	10.00	16
Krivyy (UA)	Flat continental-EU	UKDR	48.05	33.22	86
Lorient (F)	Atlantic coasts	LFRH	47.77	-3.45	44
Bergen (N)	Atlantic coasts	ENBR	60.30	5.22	50
Innsbruck (A)	Mountain areas	LOWI	47.27	11.35	593

Sofia (BG)	Mountain areas	LBSF	42.65	23.38	595

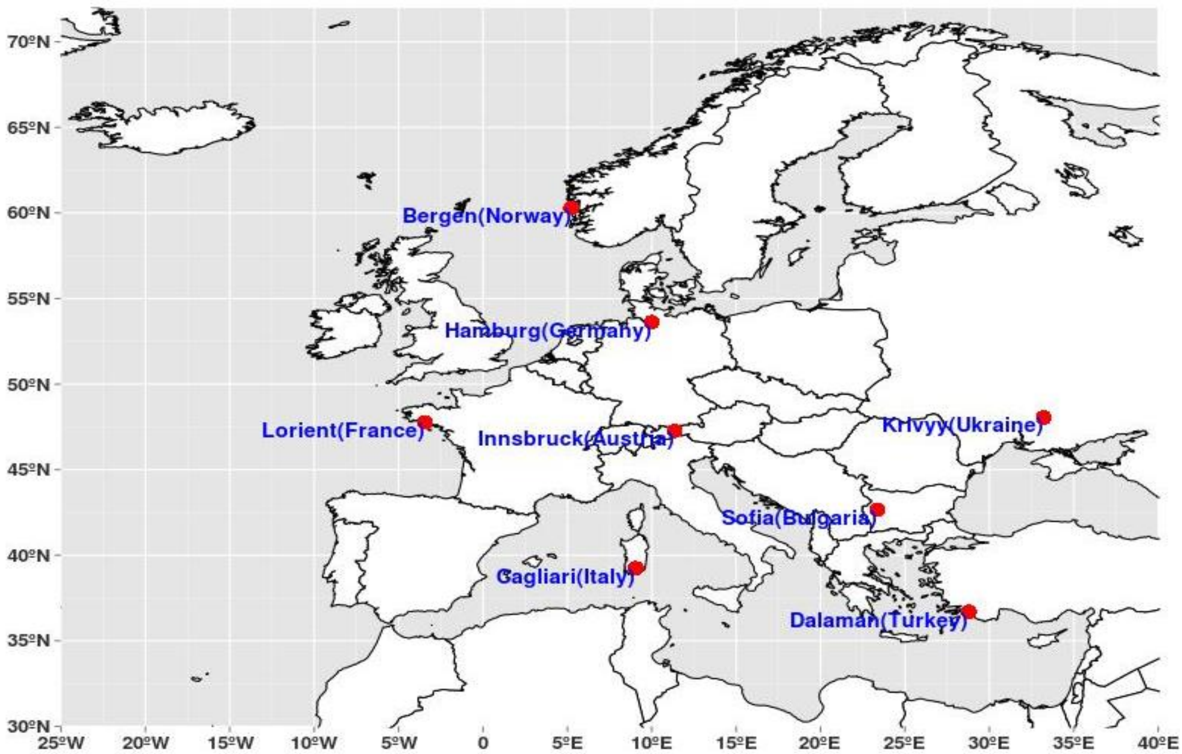


Figure 3. Selected stations for temporal data series study

3. Results and Discussion

In this section will be presented the values of the statistics parameters calculated to assess the behavior of the models in simulating the year 2010 over a European domain. As already mentioned, the model results have been compared against 371 METAR stations. Their spatial distribution covers the Atlantic coasts and flat continental and northern Europe zone until 63º of latitude. A less coverage is present in Iberian Peninsula, Scandinavian countries over 63º of latitude and Eastern Europe countries (see

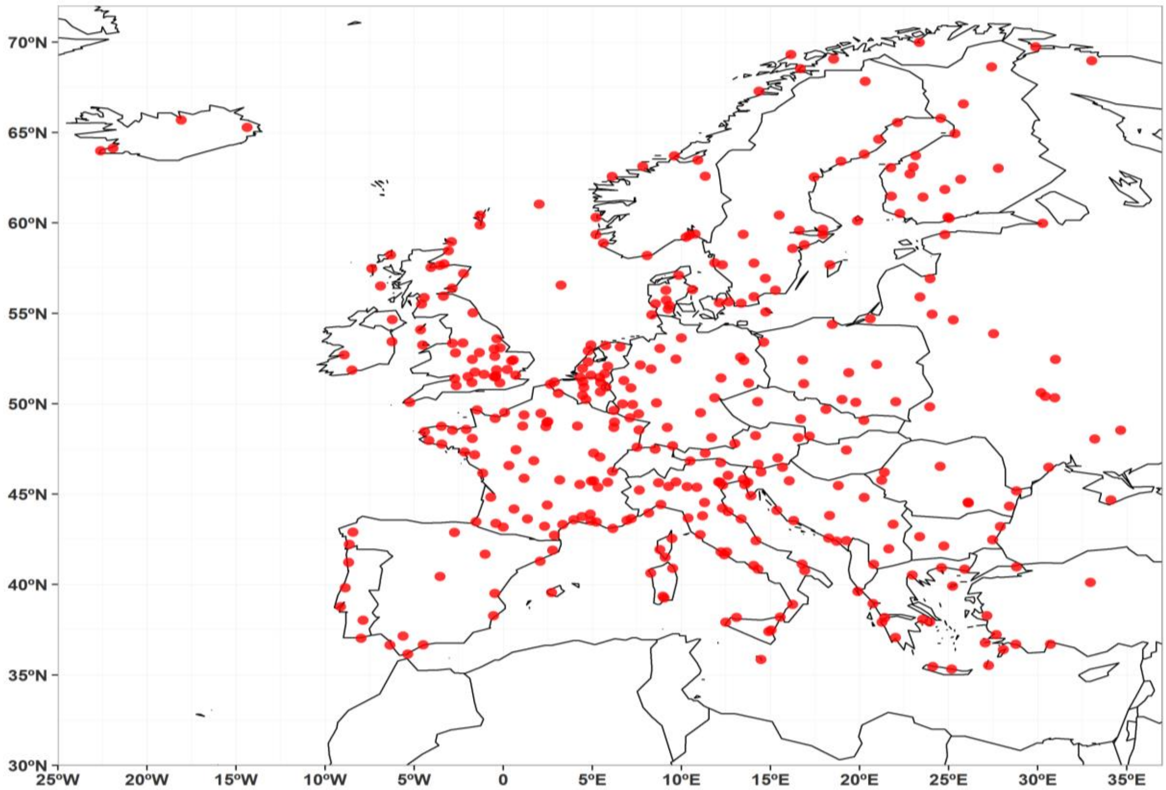


Figure 1).

3.1 Air temperature evaluation at 2 m

In **Figure 4** and **Figure 5**, are shown the annual statistic parameters (MB, r and RMSE) for all stations from the 2 simulations concerning the temperature variable. Comments are the following:

- In terms of correlation coefficient, both resolutions show good correspondence in annual values (0.94 for WRF0.44º and 0.96 for WRF25km) and monthly trend. The correlation of both simulations is a bit lower during wintertime and this performance seems to be more stressed in the WRF0.44º. The increment of horizontal resolution improves r values

mainly during winter as well as it reduces the wider dispersion of values (see **Figure 6**) that affect this period. In terms of spatial distribution, noteworthy differences appear in north of Scotland, north-west of France and in some stations over the central and eastern Mediterranean basin (see **Figure 5**).

- The WRF-0.44° resolution presents a small underestimation mainly from February to September and a small overestimation during the rest of the year (cold months). This pattern is not the same for the WRF25km as it seems to be averagely around zero for the whole year. In terms of spatial distribution, the WRF model with coarser resolution produces a greater underestimation over zone with complex topography as Balkans, Alps and over the central-eastern part of Spain. In the rest of the domain, this resolution produces MB between -1K and 2K. The WRF25 km output presents the same underestimation only over the north of Italy and eastern Iceland and in the rest of the domain there is an overestimation between 1K and 3 K. The highest MB can be noted along the Atlantic coasts of Iberian Peninsula, France and Scotland, in the Adriatic Sea as well as in the stations rising on the Black Sea.
- The error reported (RMSE) is lower for WRF25km (~2.2K) than for WRF0.44° (~3K) and the temporal trend over the reference year is the same with the exception of the warm period between April and July when the differences between two outputs are more relevant therefore the improvement due to higher resolution is more significant. On average, RMSE of WRF25km is more constant during the year with a bigger dispersion of value during the cold period. The smallest RMSE from both simulations occur during the period between August and November. The spatial distribution maps (see **Figure 5**) show higher RMSE in complex terrain areas like Iceland, Balkans and Alps regions for both simulations although this is more pronounced in the WRF0.44° resolution. Over the rest of domain (Atlantic coasts, UK, Central and Eastern Europe countries), the model gives the lowest error values (RMSE ~2K and ~3K for WRF25km and WRF0.44° respectively).

Average values for all stations	r	RMSE	MB
WRF 25 km	0.96	2.2	0.06
WRF 0.44°	0.94	2.96	-0.6

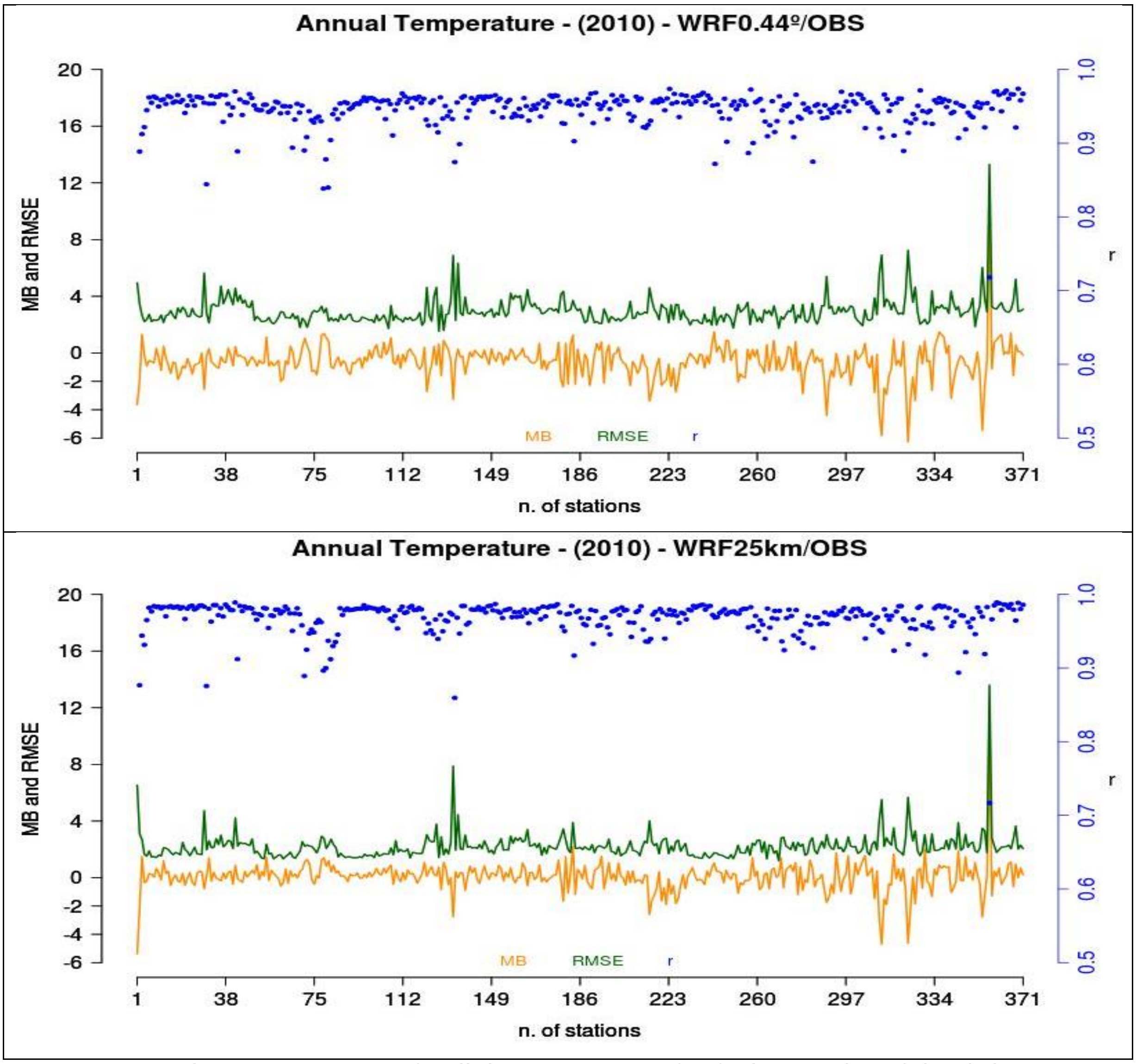


Figure 4. Annual statistic parameters for all the stations at WRF0.44º (above) and WRF25km (below)

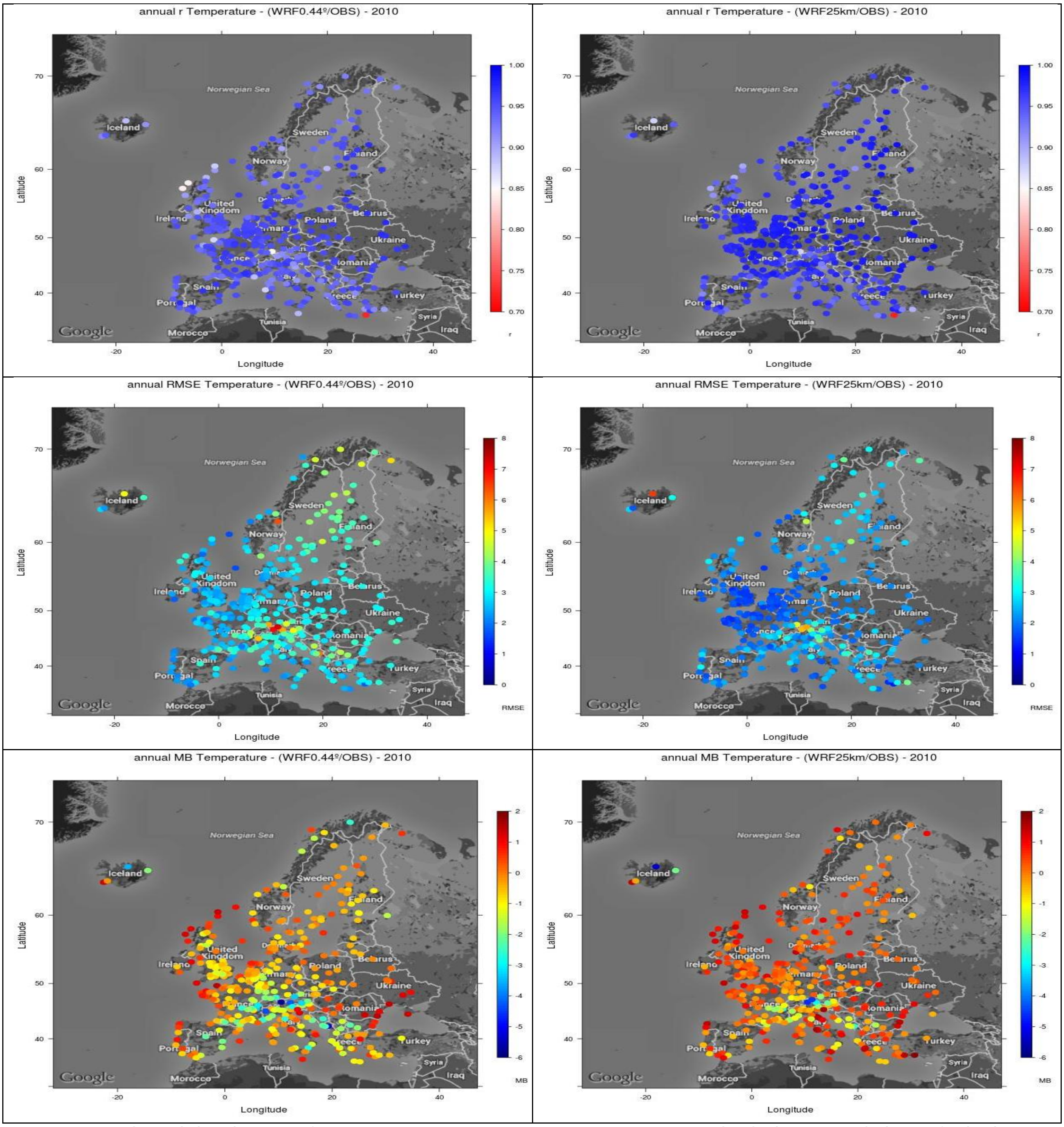


Figure 5. Spatial distributions of temperature statistic parameters (r: 1st row, RMSE: 2nd row, MB: 3rd row) for both WRF resolutions (WRF25km in left column and WRF0.44º in right column)

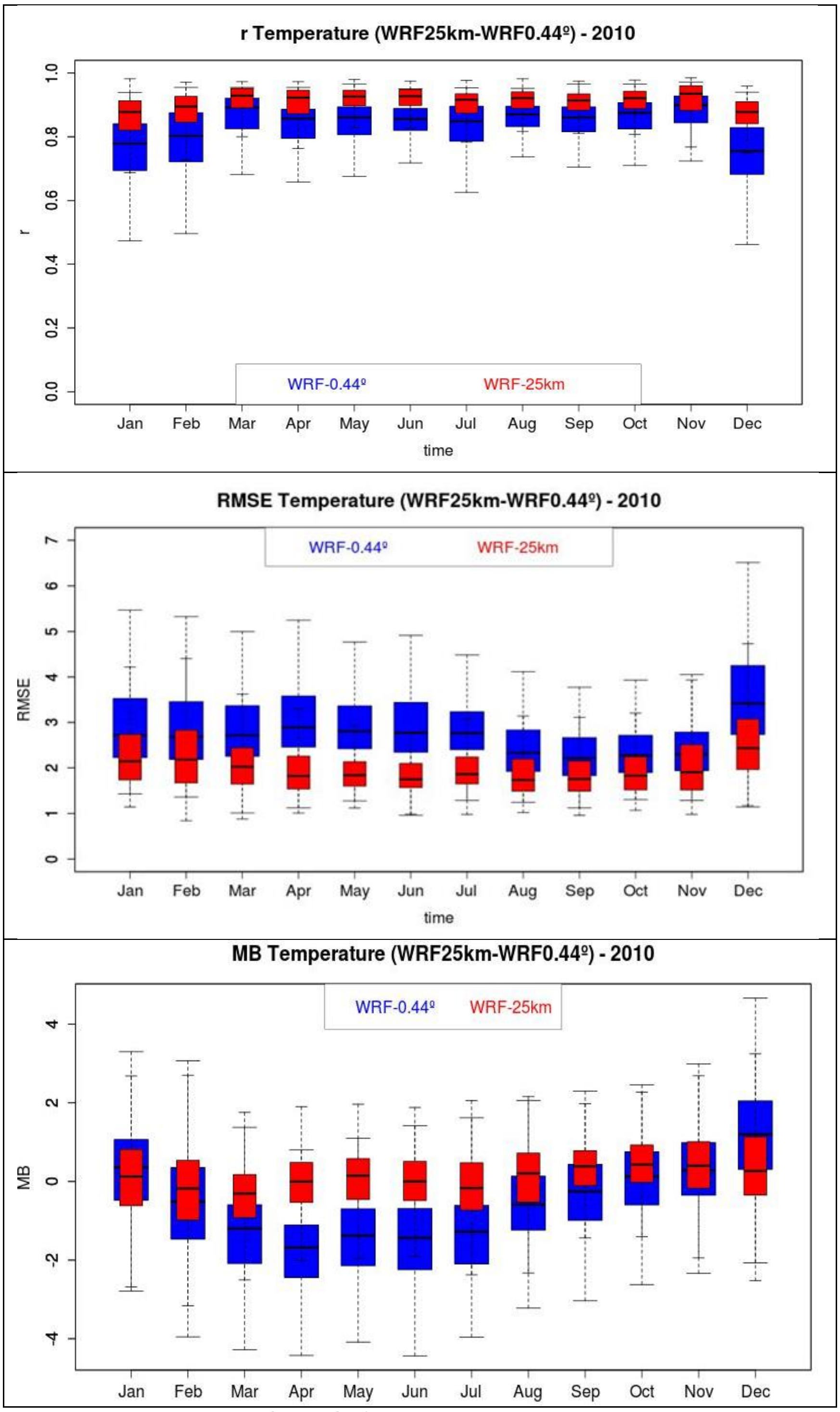


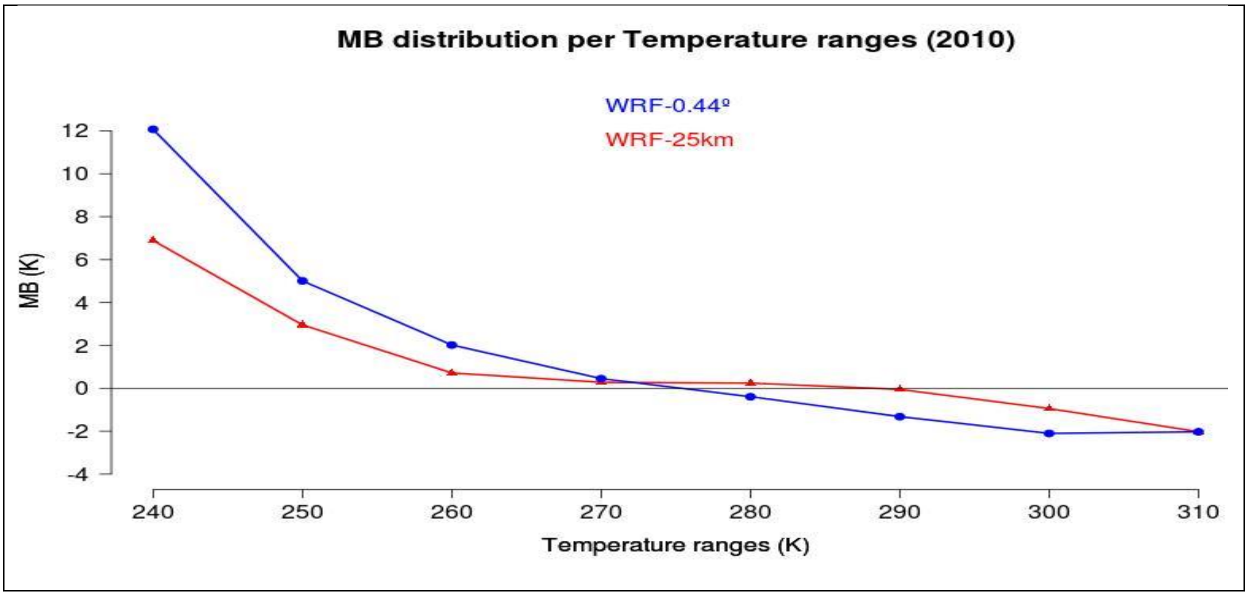
Figure 6. Annual trend of temperature statistic parameters

The Figure 7 shows MB and RMSE calculated per different temperature intervals with the intent of detailing how the different WRF resolutions operate range by range.

The MB and RMSE values presented in the following plots were computed selecting intervals of ±5K starting from 240K up to 320K. The highest temperature range (315K-325K) has not been represented because containing only 93 hourly values over 3249960 and therefore not considered representative enough.

The model tends to overestimate cold temperatures, mainly starting from 260K, and to underestimate the highest temperatures starting from 290K/300K. As already shown, the WRF25km performs better in all the selected ranges reducing the overestimation in very cold temperature (<260K) and also reducing the underestimation that occur in event of high temperature (>290K). Moreover, the increment of the spatial resolution helps improving the model output more for very cold temperature ranges (<250K) than for high temperature.

This is true also for the error where the improvements, due to higher resolution, are more notable for the lowest temperature ranges than for the highest ones. No relevant improvements occur between two resolutions over the central ranges (265K-285K).



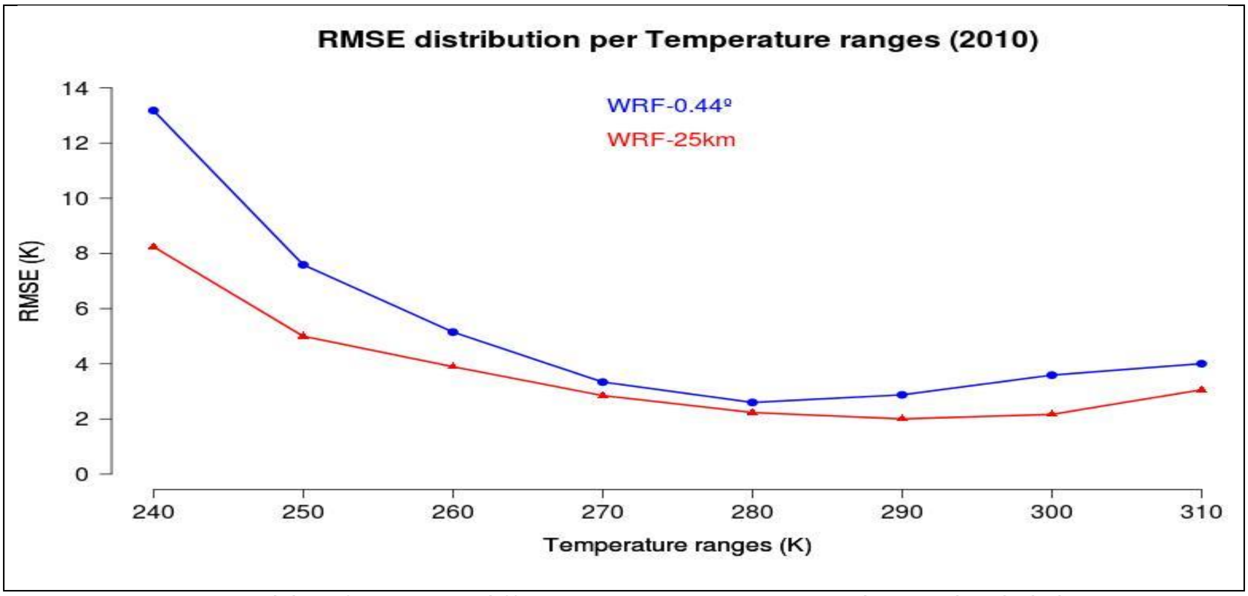
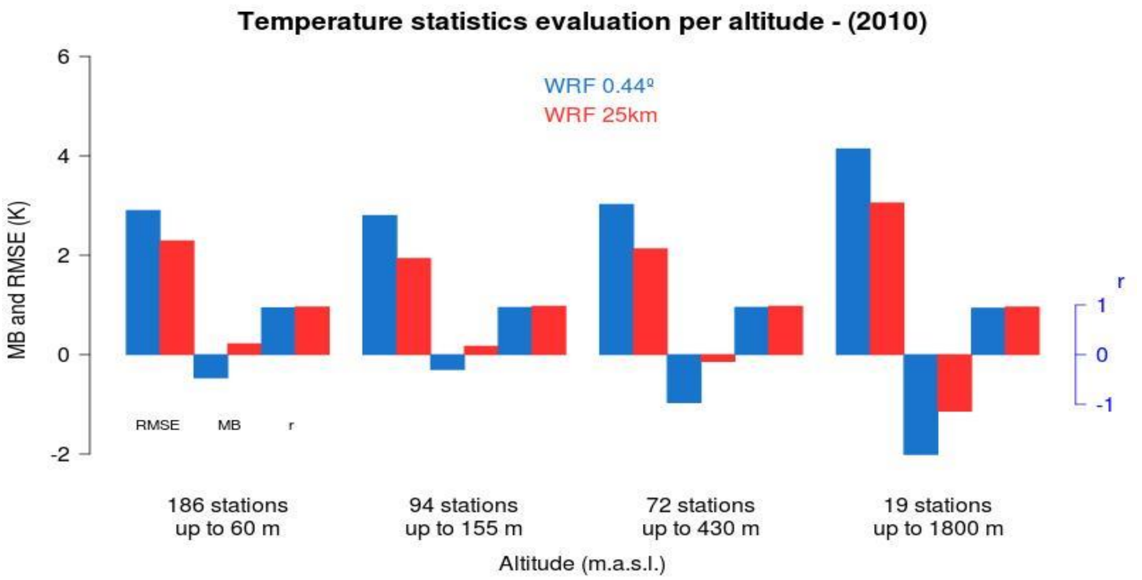


Figure 7. Model performance at different temperature ranges (MB above and RMSE below)

Finally, the variation of statistic parameters with the altitude aims to highlight specific relationships between the model results and stations elevation above sea level. The **Figure 8** shows the distribution of RMSE, MB and r for all the stations located at altitude between 0 to 60 m (186 stations), 60 to 155 m (94 stations), 155 to 430 m (72 stations) and 430 m to 1800 m (19 stations). The results indicate how the RMSE increases in both resolutions from the lowest altitude to the highest ones, although the lowest value has been reported for the 94 stations between 60m and 155m. The MB trend for the WRF 0.44º presents an underestimation that increases with the altitude starting from the second range of elevation, while the 25km resolution shows a small positive MB over flat areas and a negative MB for all the stations above 430 m. Finally, the correlation coefficient seems not be affected by the altitude for both models, in fact the values are almost constant over the 4 elevation ranges.



WRF44_MB	WRF44_RMSE	WRF44_r	WRF25_MB	WRF25_RMSE	WRF25_r	altitude
-0.467	2.900	0.942	0.219	2.289	0.962	up to 60m
-0.301	2.799	0.949	0.169	1.935	0.974	up to 155m
-0.963	3.023	0.952	-0.139	2.133	0.973	up to 430m
-2.010	4.141	0.936	-1.134	3.054	0.961	up to 1800m

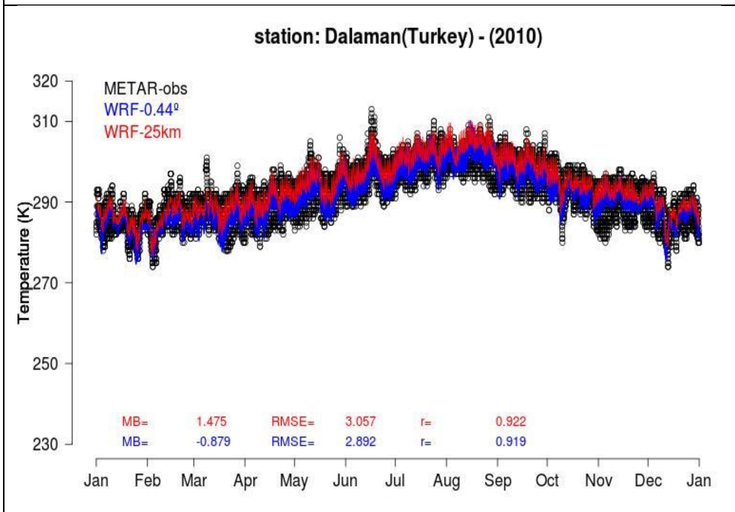
Figure 8. Annual RMSE, MB and r of temperature in function of METAR stations altitude (values in the table)

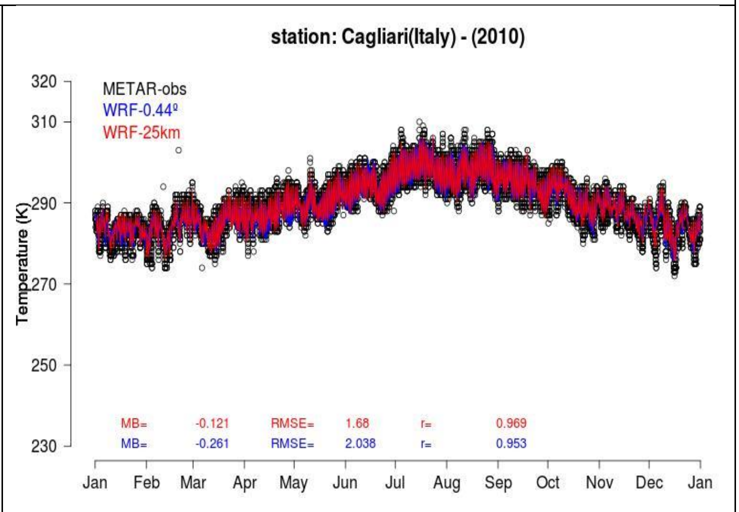
3.1.1 Temperature evaluation in the selected stations

The Figure 9 show temporal series of the air temperature for the selected stations presented in Figure 3. As mentioned before, 2 cover the Mediterranean basin, 2 are located across the flat central and east Europe, 2 are stations located along Atlantic coasts and 2 over mountain regions as Alps and Balkans. Both resolutions well reproduce the annual temporal variation and the statistics parameters respect the spatial analysis showed before. The WRF 25km resolution is able to approximate the observations better than the coarser resolution in all stations. The selected stations show a local and direct connection between temperature and complexity of terrain surrounding the stations them-selves as it is clear the worst model performances in mountain stations in front of stations located in flat or not complex topography. The highest MB and RMSE values are estimated in the stations of Innsbruck and Sofia and, although both are in mountain areas, Innsbruck is worse than Sofia, probably due to the different structure of mountain chain and valleys surrounding the cities.

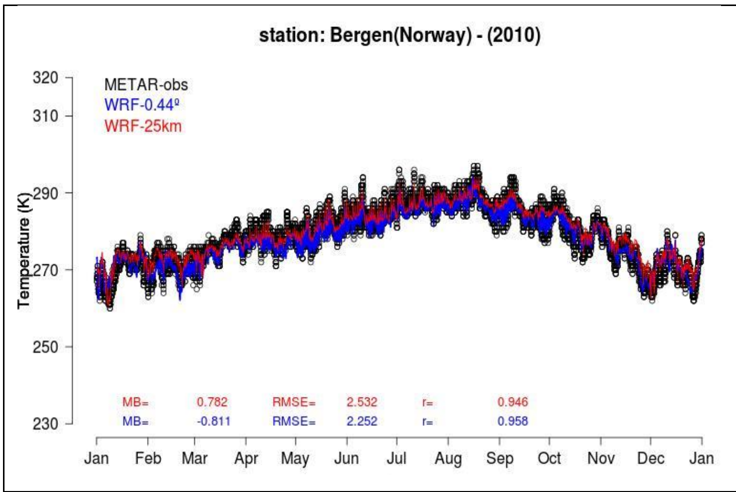
From this analysis, it seems doesn't exist a direct connection or some differences between the temperature simulated over the Atlantic stations against those located in the Mediterranean basin.

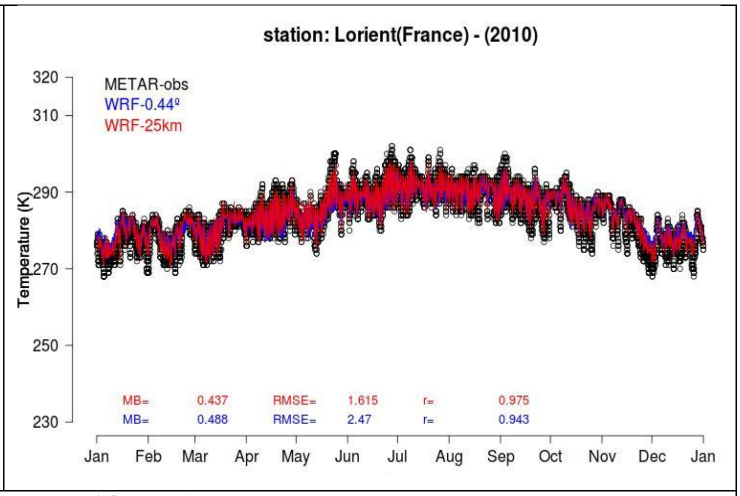
Mediterranean coasts METAR stations



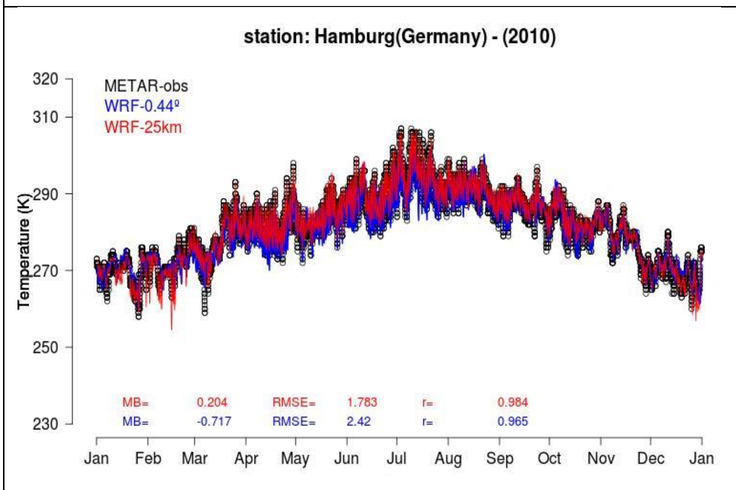


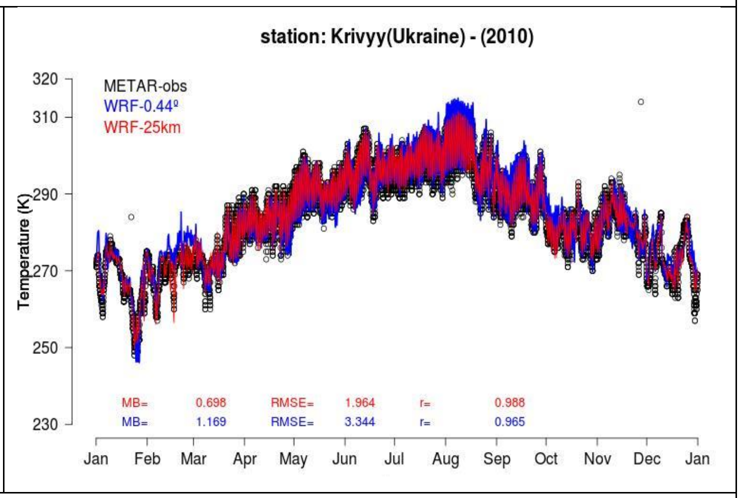
Atlantic coasts METAR stations



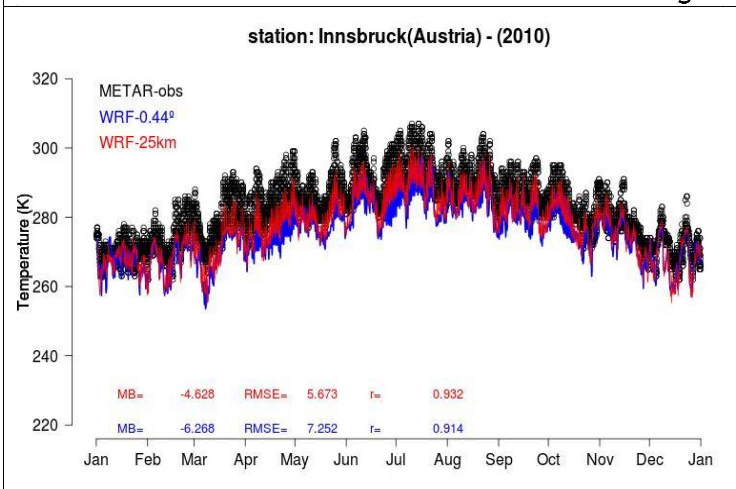


Flat continental-EU METAR stations





Mountain regions METAR stations



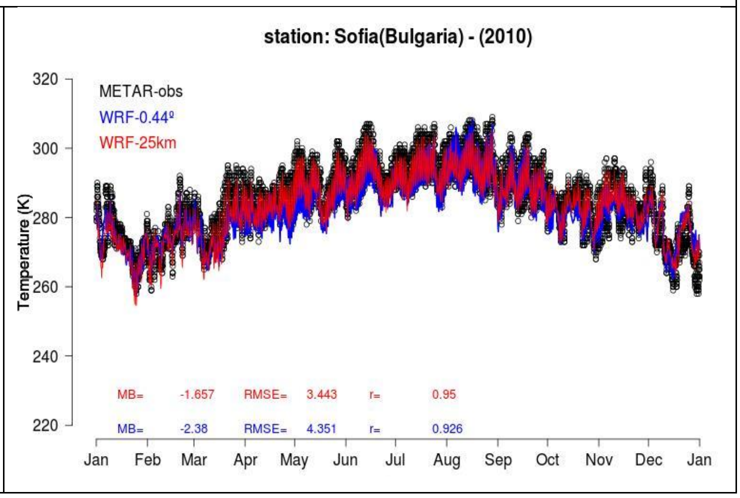


Figure 9. Temperature time series for the selected stations over three different zones

The following plot (**Figure 10**) aims to represent the annual trend of temperature statistic parameters, for both resolutions, highlighting the differences among each geographic zone. The 8 stations were grouped two by two with 4 different colors:

- *black line* for mountain regions stations
- *blue line* for Mediterranean coasts stations
- *red dotted line* for flat continental stations
- *green dotted line* for Atlantic coasts stations

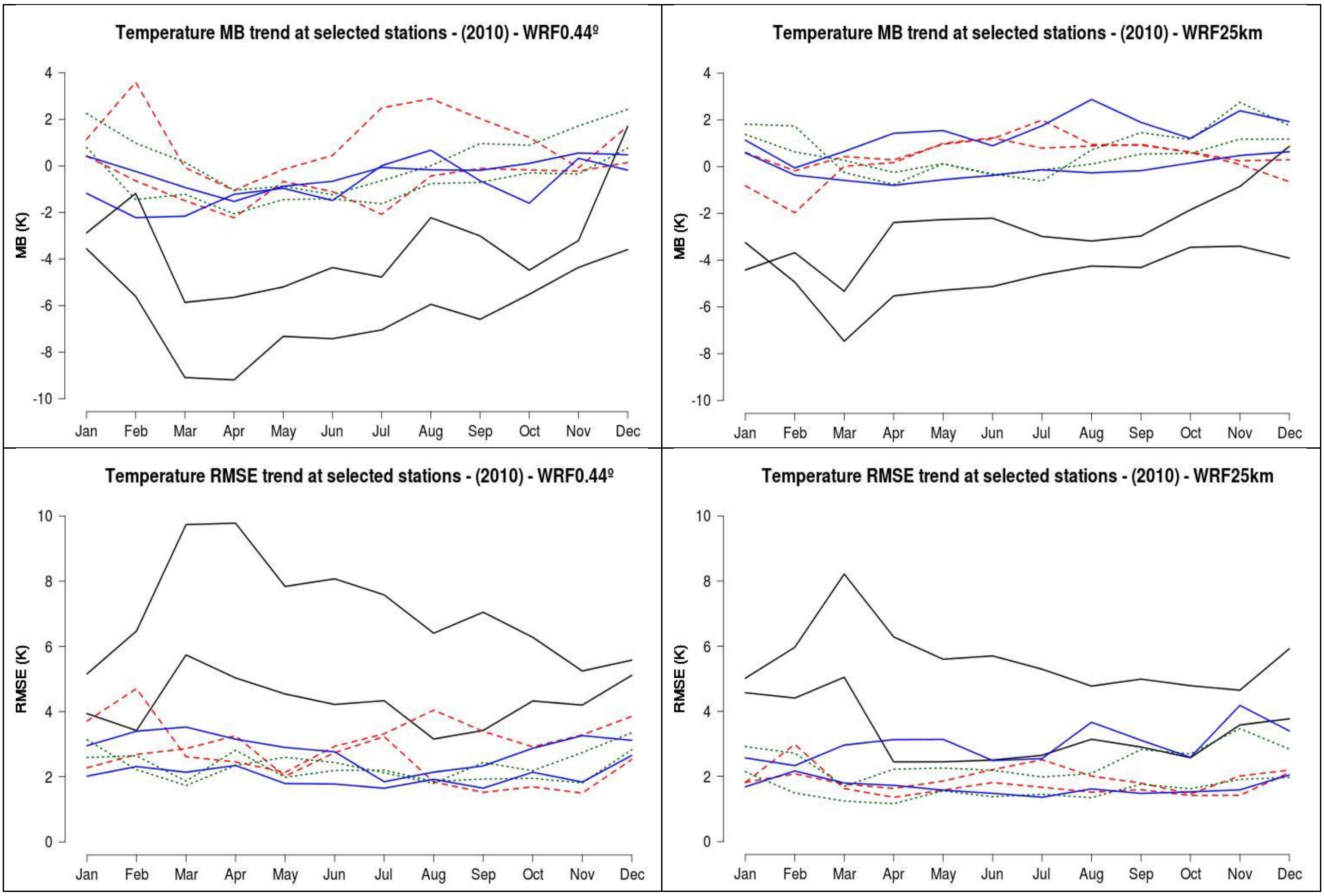


Figure 10. Temporal distribution of the temperature statistical parameters for the 8 selected stations (1st row: MB and 2nd row: RMSE)

- The improvement of resolution from 0.44º to 25km reduces the underestimation mainly over mountain regions stations while the other stations changed from a slight negative bias to a slight positive one (< 2K). Moreover, the finest resolution seems to give a bias less fluctuating during the year that means a less dispersion of values.

- The RMSE is considerably reduced for both mountain regions stations although is preserved the temporal trend (greater error during cold months). A slight error decrement is also notable over flat and Atlantic regions.
- The highest resolution simulation produces curves more closer to each other within the same type of stations (e.g. see the 2 Atlantic stations or the 2 flat region stations), if compared with the WRF0.44º output and this might be due to a more realistic and detailed interpretation of the local conditions (topography, position of the station, buildings or other local factors).

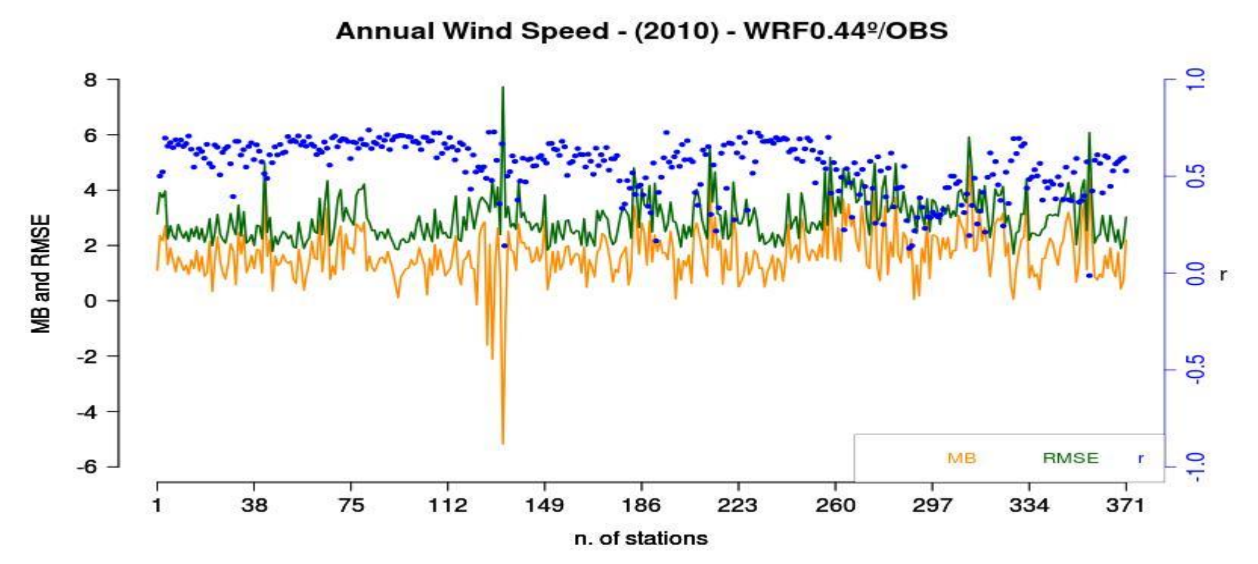
3.2 Wind speed evaluation at 10 m

It will be discussed now the wind speed evaluation at 10 m height simulated by the model. In **Figure 11** and **Figure 12**, are shown the annual statistic parameters (MB, r and RMSE) for all stations from the 2 simulations concerning the wind speed variable. Comments are the following:

- The correlation coefficient for both resolutions, show quite good values although the difference is more relevant between the resolutions (0.55 for WRF0.44º and 0.7 for WRF25km). The monthly correlation is quite similar over the year as the WRF25km values present a less dispersion than ones from WRF0.44º. In terms of spatial distribution both results present the lowest affiliation mainly over areas characterized by complex topography such as Alpen and Balkans regions but in general in all the stations located in the Mediterranean basin. In the WRF0.44º simulation map, this behavior is more marked (r = 0.2, 0.3) over all Mediterranean basin and along Norwegian coasts (see **Figure 12**).
- Both resolutions produce a weak annual over estimation of 1.17 m/s and 1.67 m/s for WRF25km and WRF0.44º respectively. The annual trend shows that during cold months the MB is higher and presents a wider dispersion of values probably due to high wind speed events or a misrepresentation of continental anticyclone that may produce atmospheric stability (especially during cold periods), while during the summertime we have the minimum with also a less dispersion of values. The spatial distribution indicates relevant over estimation by the WRF0.44º mainly located in the Mediterranean area and over the north-western of Europe (Scotland, Norway and Iceland) that probably depends on the peculiar morphology of the basin, with complex coastal profiles and local wind re-circulation not understood by the coarser resolution. The WRF0.44º in fact, gives higher MB values (up to 4 m/s) over Italy, Iberian Peninsula, Balkans countries, and Greece. This moderate overestimation is reduced in the WRF25km output to values ≥ 2 m/s in south and north-western Europe as well as over the flat continental Europe (≤ 1 m/s).

- The estimated annual RMSE is lower for WRF25km (2.24 m/s) than for WRF0.44º (2.98 m/s) and both simulations show they have the same monthly distribution over the year. In fact, in winter the RMSE is higher with a wider dispersion of values, and vice-versa during the summertime. The spatial distribution maps show higher RMSE (up to 4-6 m/s) from WRF0.44º in complex terrain zones mainly located in the Mediterranean areas (Italy, south of Spain and Balkans areas) but also in Scotland, Iceland and Norway, probably due to the same causes discussed above. In the WRF25km simulation, this error is reduced mainly over the Northern European countries, while it persists over some locations in south of Italy and eastern Mediterranean Sea.

Average values for all stations	r	RMSE	MB
WRF 25 km	0.7	2.24	1.17
WRF 0.44º	0.55	2.98	1.67



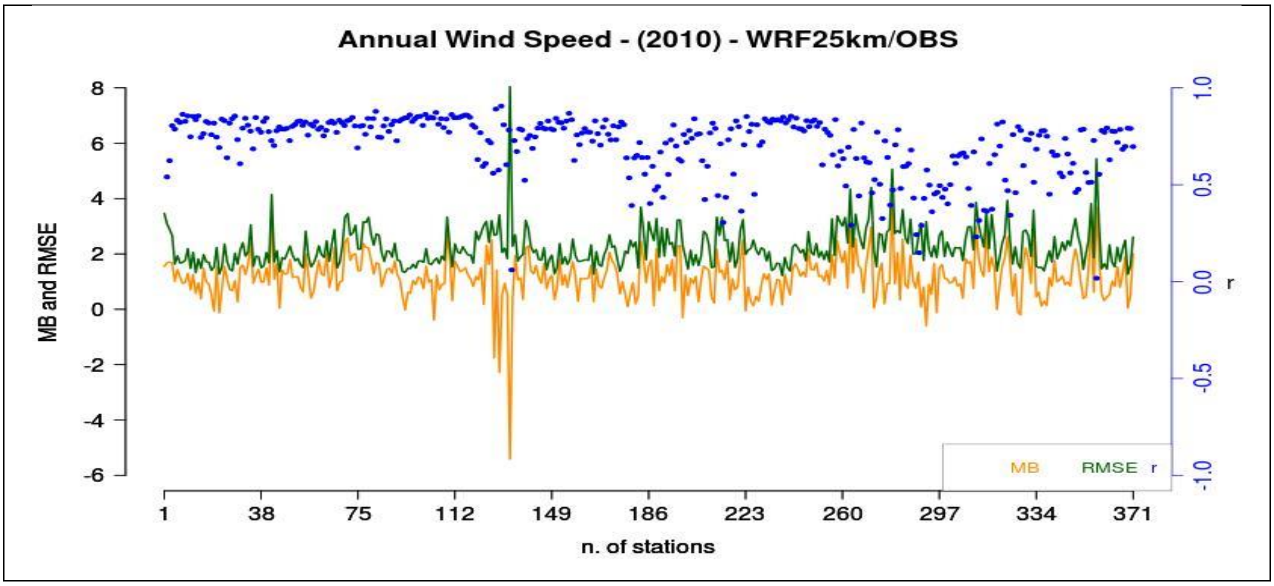


Figure 11. Annual statistic parameters for all the stations at WRF0.44º (above) and WRF25km (below)

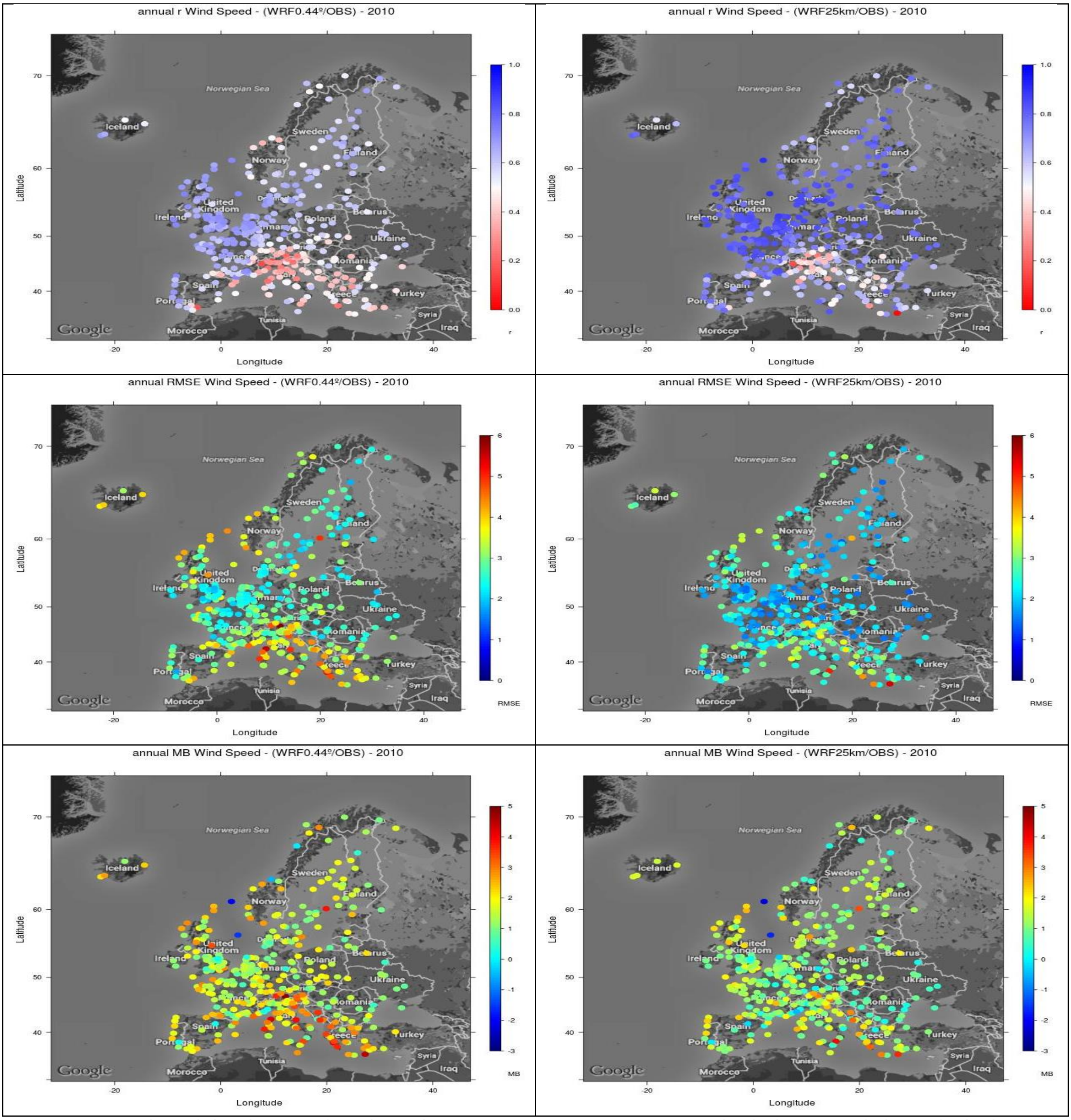


Figure 12. Spatial distributions of wind speed statistic parameters (r: 1st row, RMSE: 2nd row, MB: 3rd row) for both WRF resolution (WRF25km in left column and WRF0.44º in right column)

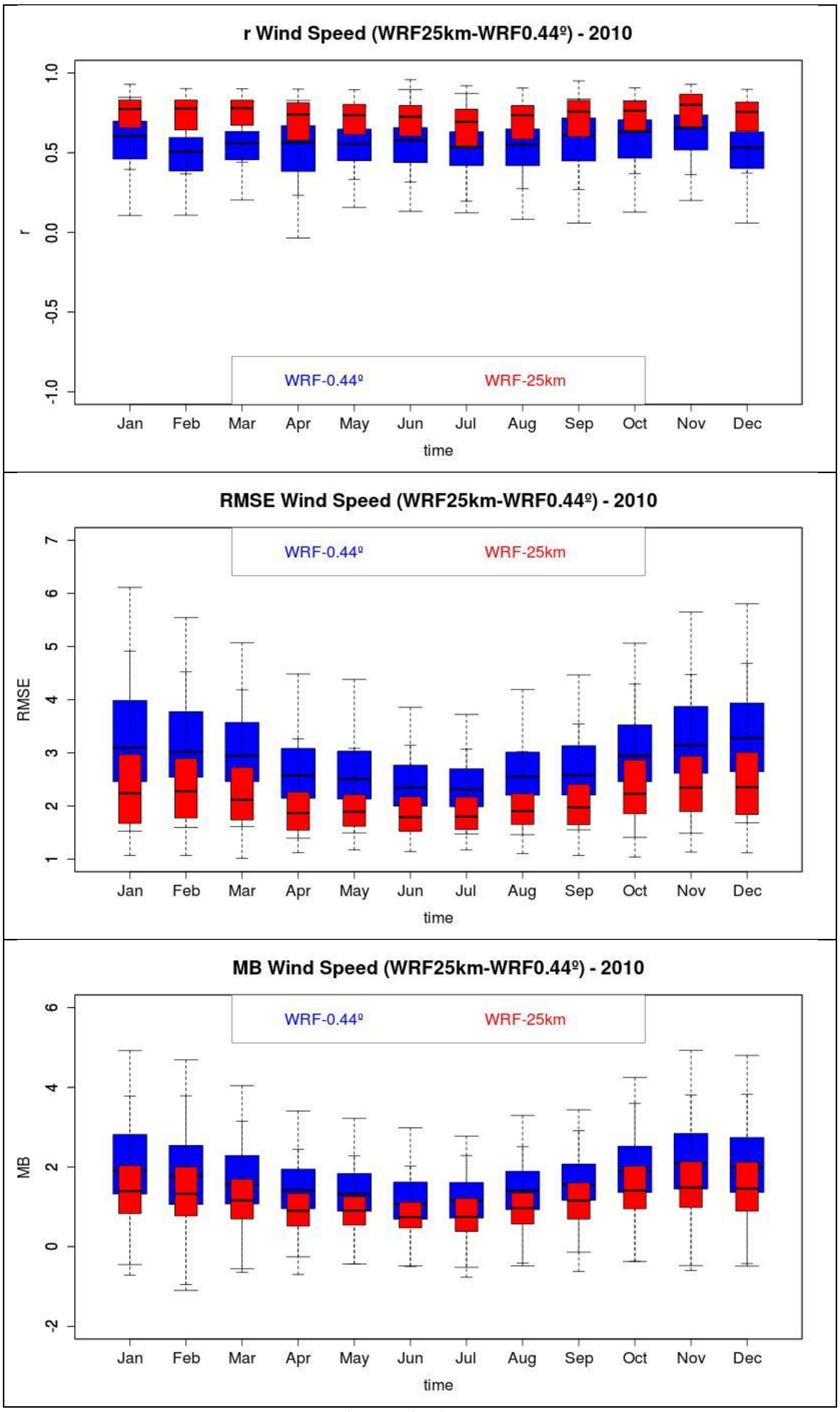


Figure 13. Annual trend of statistic parameters

The MB and RMSE values presented in **Figure 14** were computed selecting an interval of ±0.5 m/s starting from 0.5 m/s up to 14 m/s. The model at both resolutions clearly shows a tendency to overestimate low and medium wind speed ranges (up to 9.5m/s - 10 m/s), while are underestimated the highest speed ranges (from 10 m/s to 14 m/s). The error is the minimum in the medium speed ranges, and maximum in event of wind calm or strong winds, which show clear difficulties of the model in reproducing the events.
Increasing the model resolution allows for reducing the MB in both low and high speed ranges, although is a little bigger the gap between WRF25km and WRF0.44º curves over the first ranges (between 0.5 and 3.5 m/s). The error is clearly reduced by the WRF25km over all the selected ranges but this improvement is more visible with low wind speeds values (up to 4 m/s).

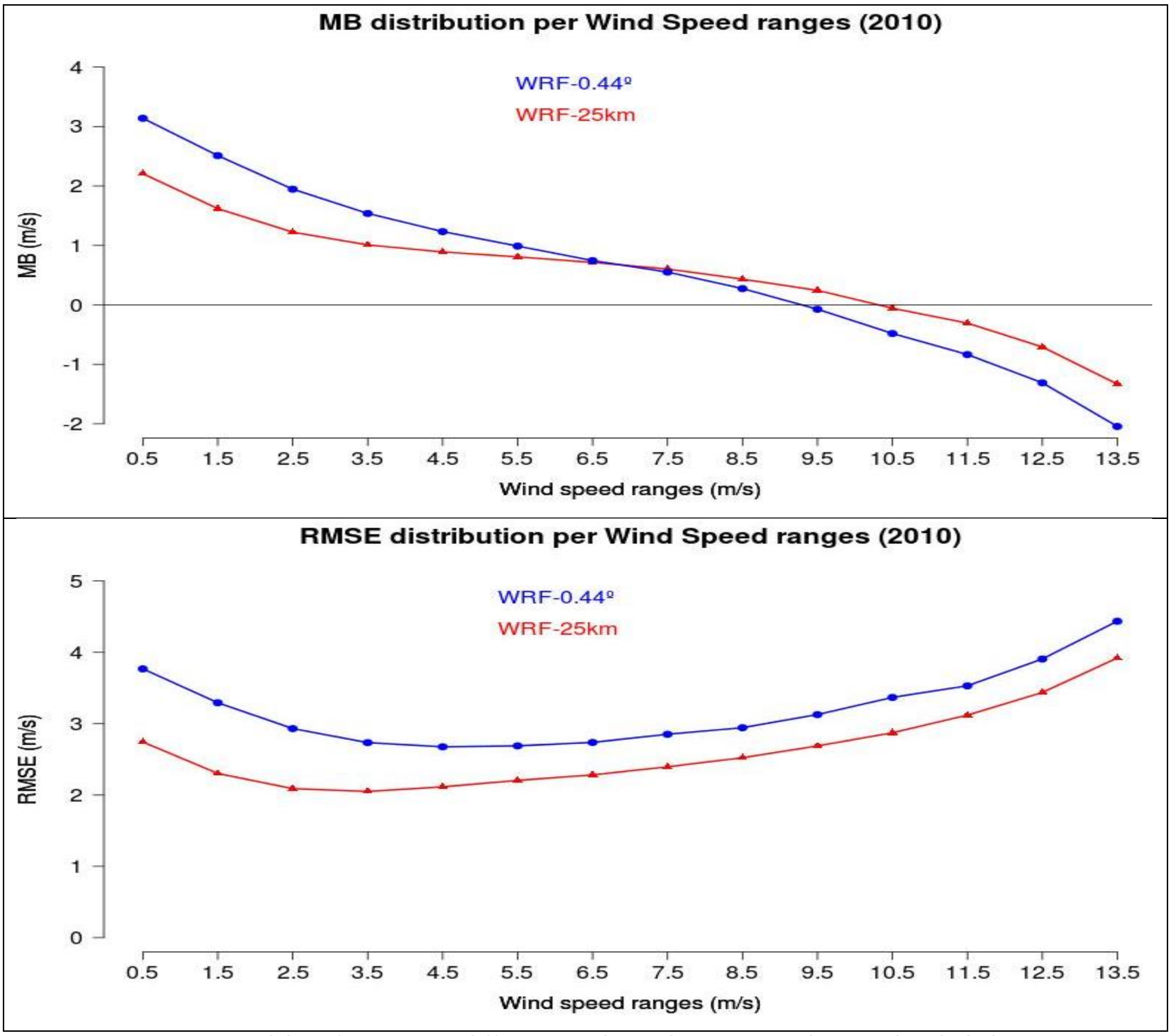
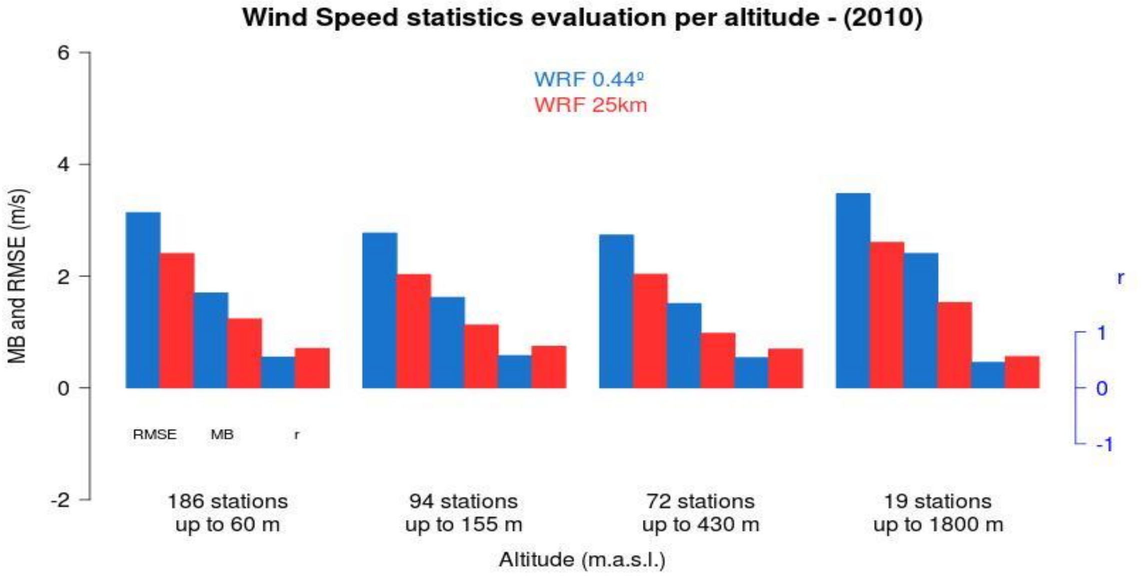


Figure 14. Model performance at different wind speed ranges (MB above and RMSE below)

The

WRF44_MB	WRF44_RMSE	WRF44_r	WRF25_MB	WRF25_RMSE	WRF25_r	altitude
1.699	3.135	0.552	1.235	2.403	0.705	up to 60m
1.619	2.770	0.578	1.126	2.028	0.744	up to 155m
1.509	2.734	0.543	0.977	2.033	0.697	up to 430m
2.406	3.475	0.458	1.527	2.603	0.561	up to 1800m

Figure 15 shows the trend of RMSE, MB and r for all the stations located at the same ranges of altitude presented before. The results indicate a moderate increment of RMSE and MB that occur only with stations within the highest range of altitude (between 430 and 1800m). The highest performance of the model seems to be produced with the 94 stations between 60m and 155m in altitude. Finally, the correlation coefficient seems to be the most affected parameter by the altitude for both models in a way that is more notable in the WRF25km simulations.



WRF44_MB	WRF44_RMSE	WRF44_r	WRF25_MB	WRF25_RMSE	WRF25_r	altitude
1.699	3.135	0.552	1.235	2.403	0.705	up to 60m
1.619	2.770	0.578	1.126	2.028	0.744	up to 155m
1.509	2.734	0.543	0.977	2.033	0.697	up to 430m
2.406	3.475	0.458	1.527	2.603	0.561	up to 1800m

Figure 15. Annual RMSE, MB and r of wind speed in function of METAR stations altitude (in the table are showed the values)

3.3 Wind direction evaluation at 10 m

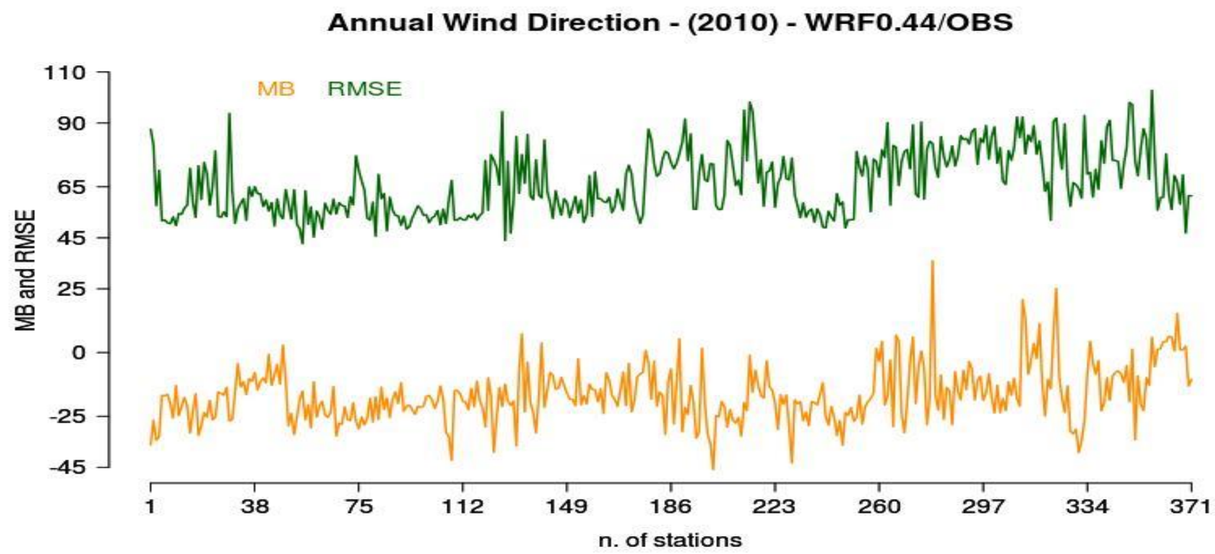
The wind direction is probably the most complex meteorological variable (among those analyzed here) to analyze in terms of spatial and temporal distribution over a European domain. Both simulations are affected by errors in the interpretation of wind direction and dispersion of values as well. The WRF0.44º simulation tends to produce greater error and a more negative MB against the observation, if compared with the WRF simulation at higher resolution which produces a slight negative bias with an error around 50º. This type of information is not so easy to analyze over an entire continent and for a huge amount of stations in fact, the most correct analysis should be done station by stations as the wind direction may be strongly influenced by topography, obstacles and position among others.

The Figure 16 and Figure 17 show the annual statistic parameters (MB and RMSE) and their spatial distributions about the wind direction simulations (also resumed in **Error! Reference source ot found.**). Comments are the following:

- The simulations results produce an annual MB of -5.01º and -16.62º for WRF25km and WRF0.44º respectively. The negative sign of the MB means that the model is generally biased to simulate wind vectors from the left of the observations stations (anti-clockwise orientation). The temporal MB tendency (see Figure 18) is the same for both simulations outputs and shows a weak MB reduction (toward 0) during warmer months (from April to August), even becoming positive in the WRF25km simulation. The spatial distribution indicates that the coarser resolution estimates negative MB (between -30º and -15º) over the western and central Europe along all latitudes, while the MB is positive (clock-wise wind vectors) mainly over the Alps region, Greece and Eastern Europe countries. The finest WRF resolution reproduces a less negative MB (between -15º and 0º) mainly over the western and central European countries and the positive MB (from 0º up to 20º) occurs all over eastern Mediterranean basin and Eastern Europe and Finland.
- The estimated annual RMSE is lower for WRF25km (51.1º) than for WRF0.44º (66.28º) and both simulations show they have the same constant temporal trend over the year (see Figure 18), although, in the cold months the error is a little bit lower than warmer months. The spatial distribution maps show clearly that the RMSE decreases moving from the Mediterranean countries toward the northern Europe and it increases again in the stations located in Iceland and Norway. Over Spain, Italy and Balkans countries is possible to note the highest error values (90º-100º and 70º-80º for WRF0.44º and

WRF25km respectively) while the lowest ones are well distributed over central and north Europe (~50º and ~30º for WRF0.44º and WRF25km respectively). These patterns might depend on the complex topography of the Mediterranean countries and by the strong wind conditions over the Norwegian Sea.

Average values for all stations	RMSE	MB
WRF 25 km	**51.1**	**-5.01**
WRF 0.44º	**66.28**	**-16.62**



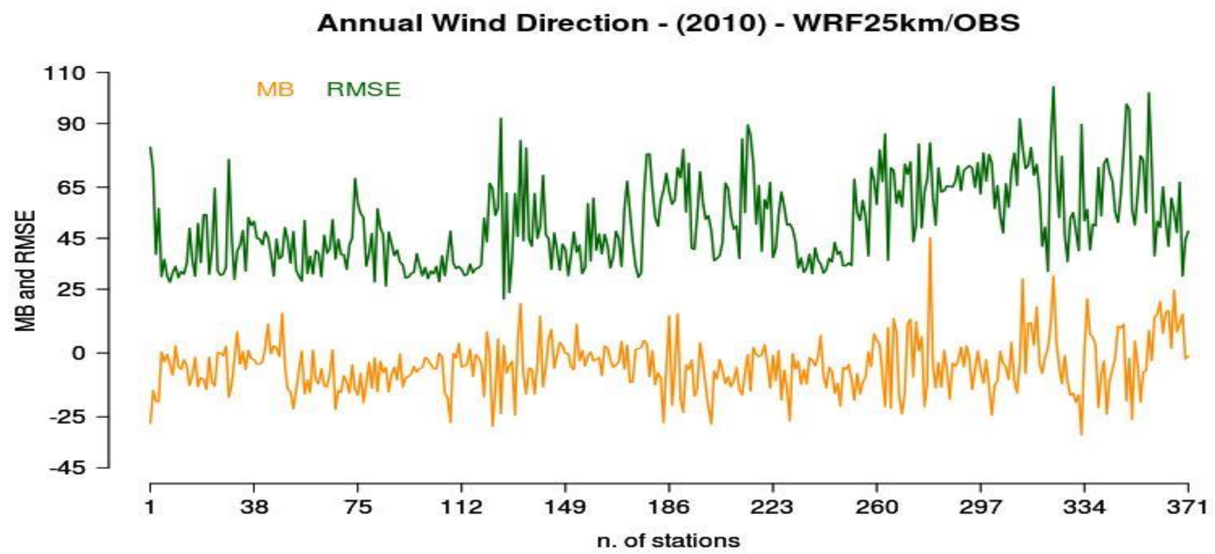


Figure 16. Annual statistic parameters for all the stations at WRF0.44º (above) and WRF25km (below)

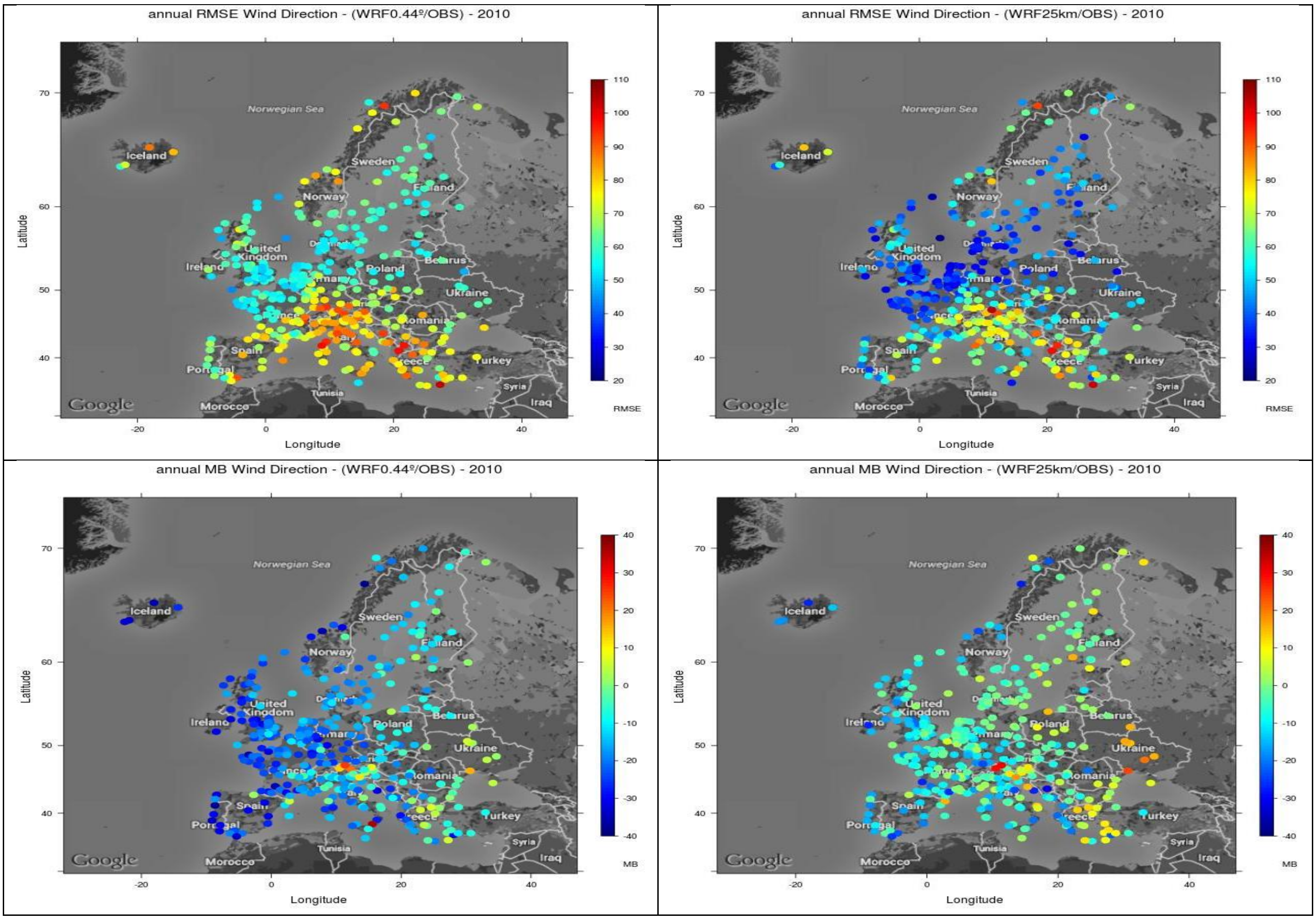
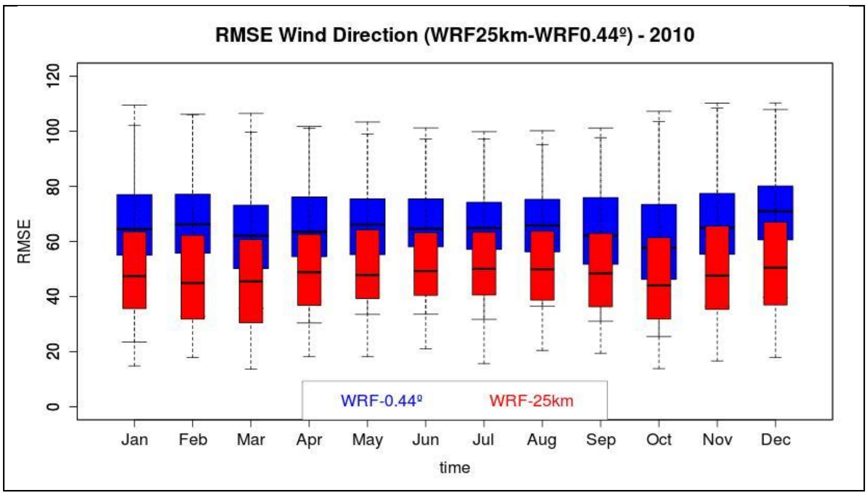


Figure 17. Spatial distributions of wind direction statistic parameters (RMSE: 1st row, MB: 2nd row) for both WRF resolution (WRF25km in left column and WRF0.44º in right column)



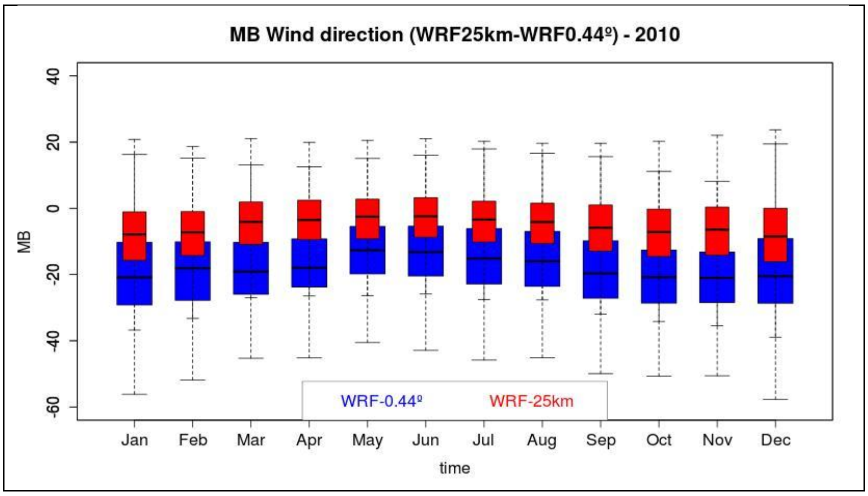
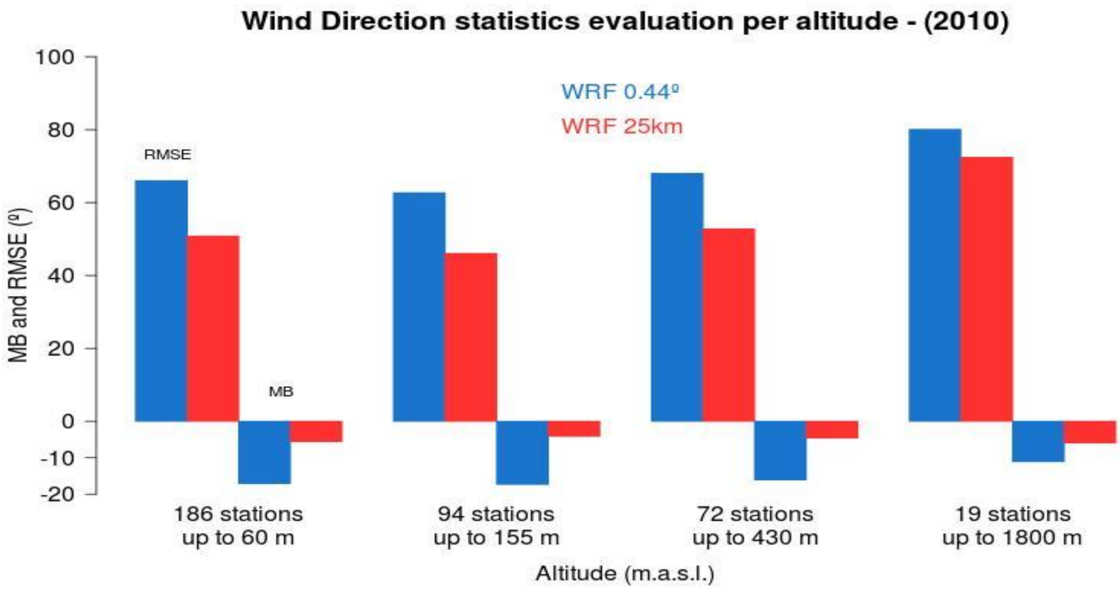


Figure 18. Annual trend of statistic parameters

The **Figure 19** shows the relationship between RMSE and MB values against the altitude for the wind direction for all the stations located within the ranges of elevation already mentioned. The results indicate a moderate increment of RMSE with the altitude even though the lowest values is not in correspondence of the 1st group (stations at elevation less than 60 m) but in the 2nd one (stations at elevation between 60m and 155 m), this pattern is true for both WRF resolutions. The MB values trend for the WRF0.44 simulation present a clear reduction with the altitude (from -17.06 to -11.05) that indicate the model reduce its wind vectors anti-clockwise orientation over complex terrains although this is not true for the WRF25km resolution which seems not be sensible with the altitude variation.



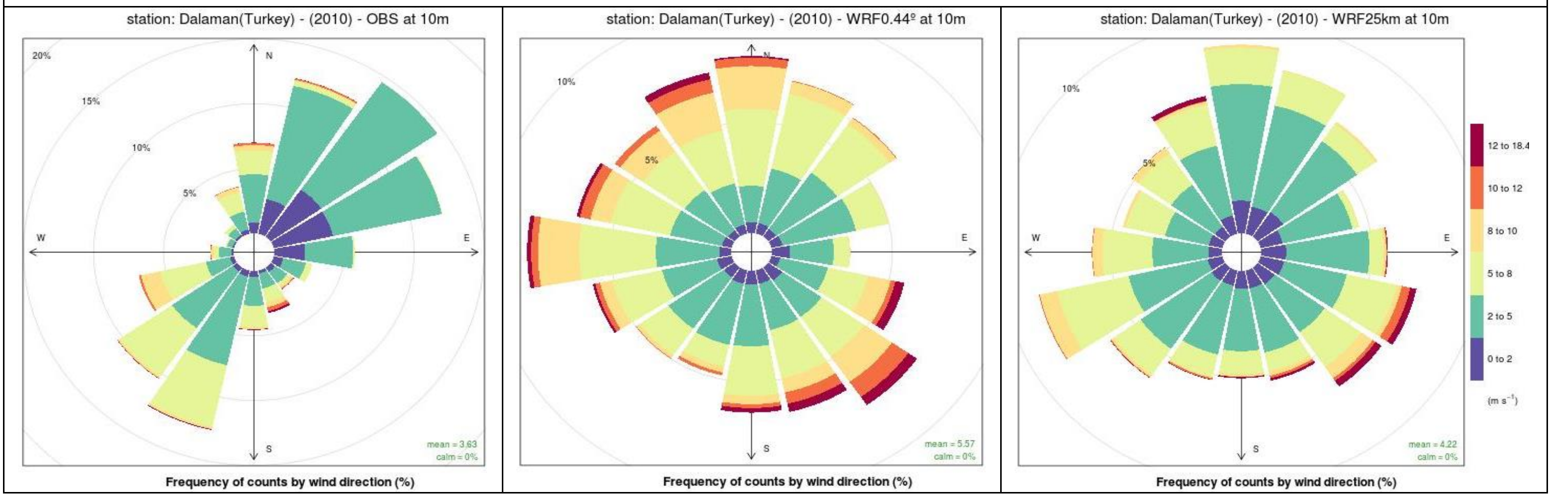
WRF44_MB	WRF44_RMSE	WRF25_MB	WRF25_RMSE	altitude
-17.067	66.022	-5.558	50.824	up to 60m
-17.321	62.699	-4.095	46.055	up to 155m
-16.036	67.999	-4.576	52.774	up to 430m
-11.051	80.112	-5.944	72.413	up to 1800m

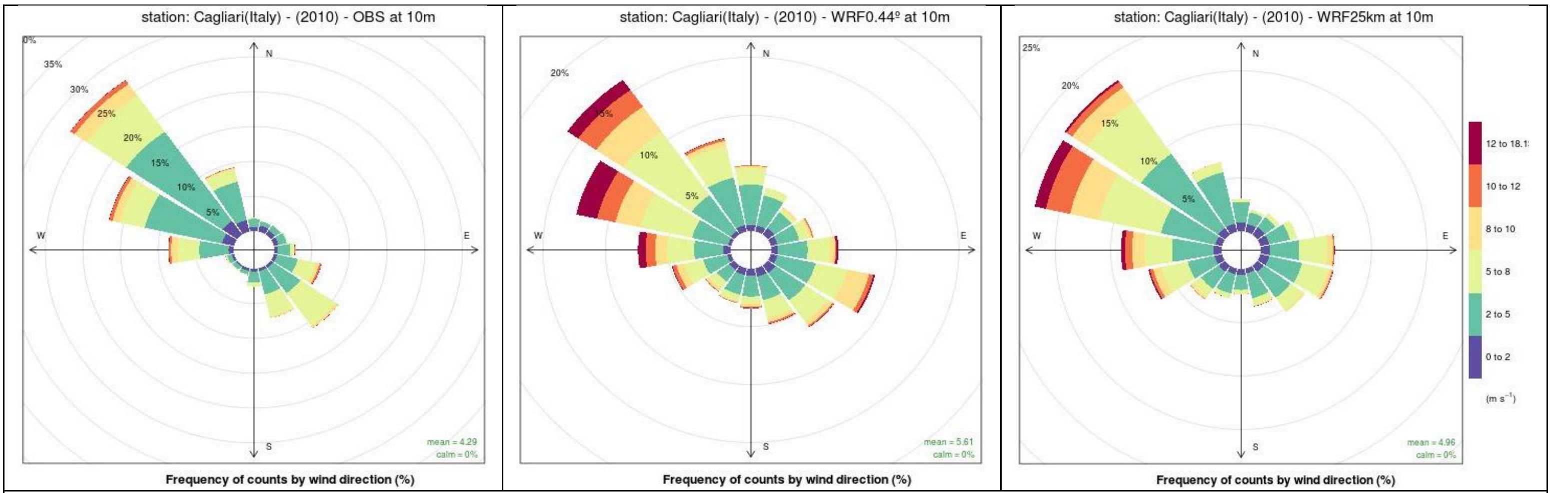
Figure 19. Annual RMSE and MB of wind direction in function of METAR stations altitude (in the table are showed the values)

3.3.1 Wind speed and direction evaluation in the selected stations

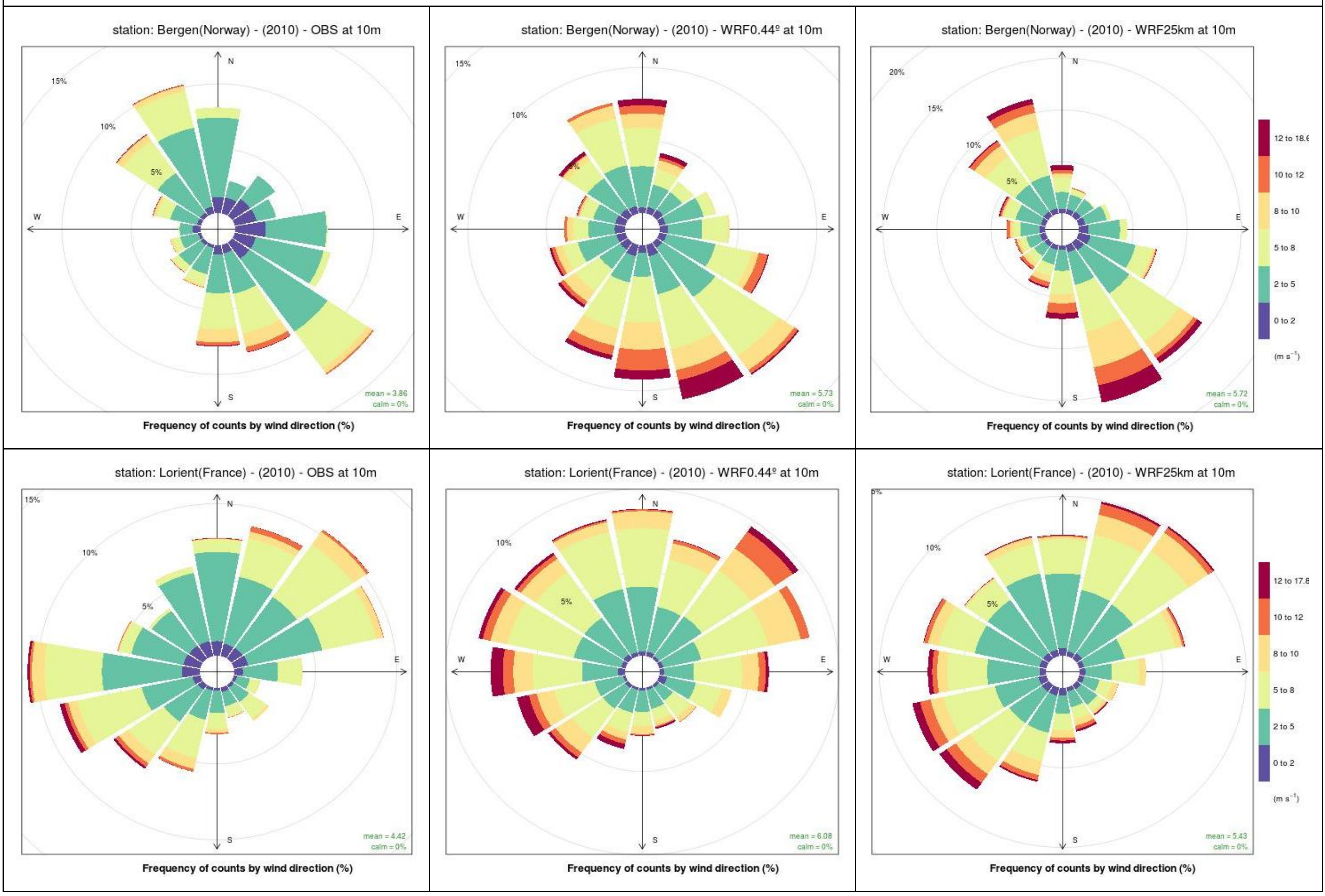
Figure 20 compares wind roses from both resolutions dataset against observations to assess the model skills in reproducing wind directions and speeds in particular places. The best model performance is found over both flat continental interiors and the Atlantic coasts in reproducing the dominant wind direction and speed. The WRF25km resolution operates better than the 0.44º as it is able to better adjust the sea/land interfaces, the orography and the mesoscale circulations, leading to improve the simulated winds.
Concerning the lowest wind speed range (below 2 m/s), both resolutions reproduce quite well the directions but underestimate the velocity amount.
The mountain stations are the worst represented by the model as the observations clearly represent two dominant wind directions mainly in the east-west axis, surely due to the natural orientation of the valleys, while the model in both stations has simulated winds mainly from south or south-west direction. Moreover, as the wind roses of these 2 stations are very similar at both resolutions although they are far from each other, it probably means that this error is systematic in how the model assesses the wind parameters.
Finally, the increment of the horizontal resolution seems to give more benefits in the Atlantic coasts stations than over the Mediterranean ones, although as known, the speed is constantly overestimated.

Mediterranean coasts Metar stations

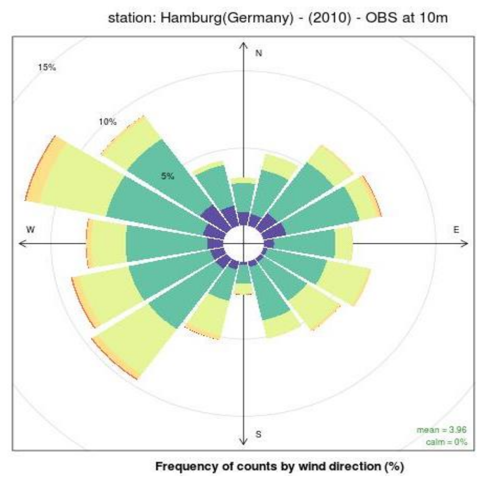


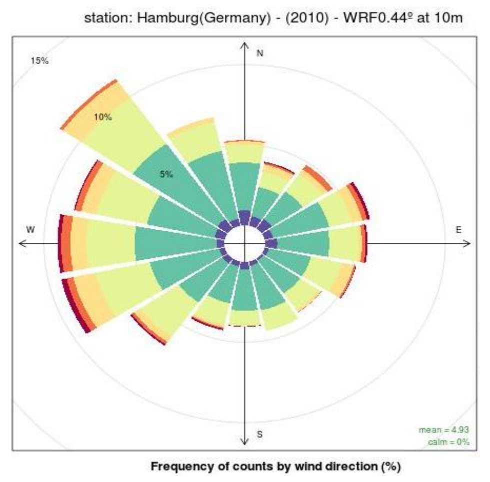


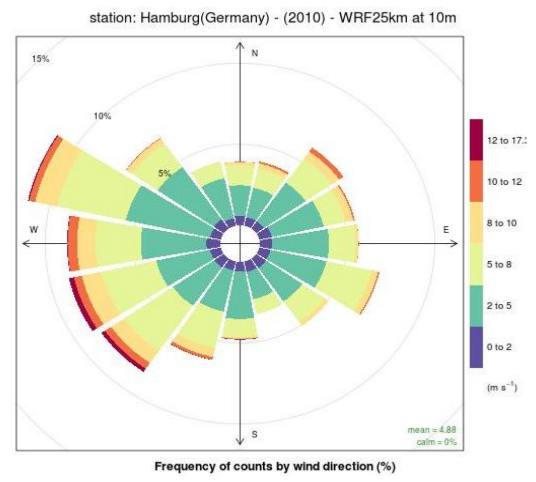
Atlantic coasts Metar stations

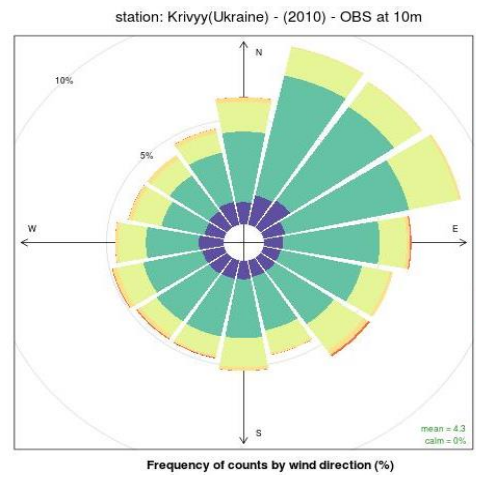


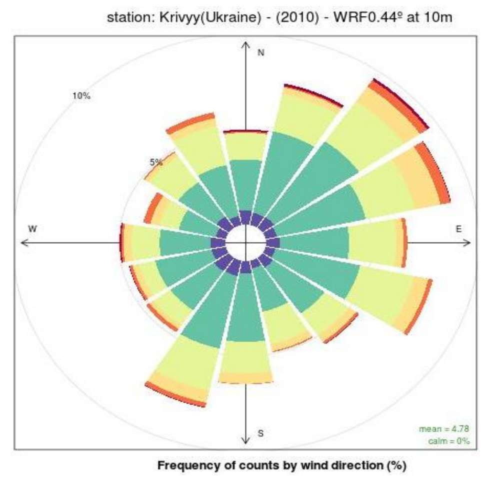
Flat continental Europe

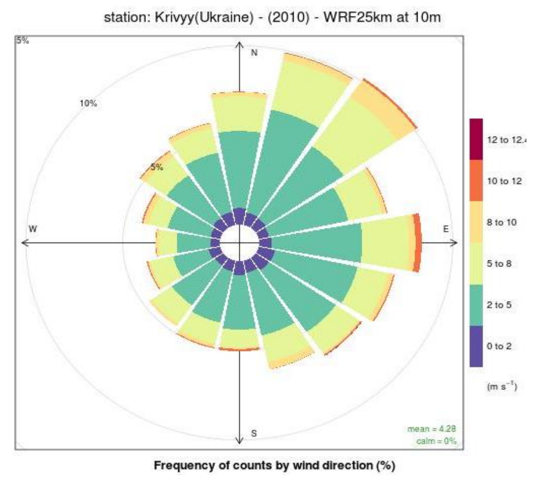




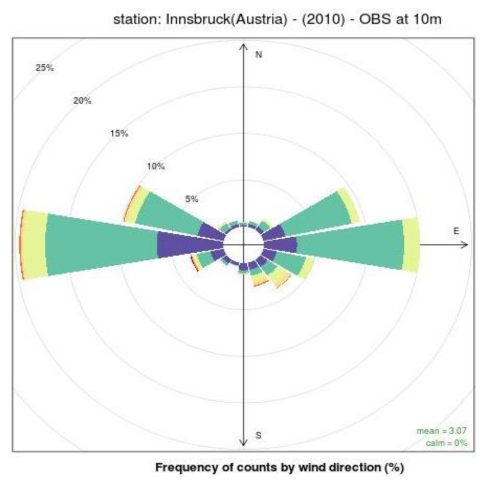


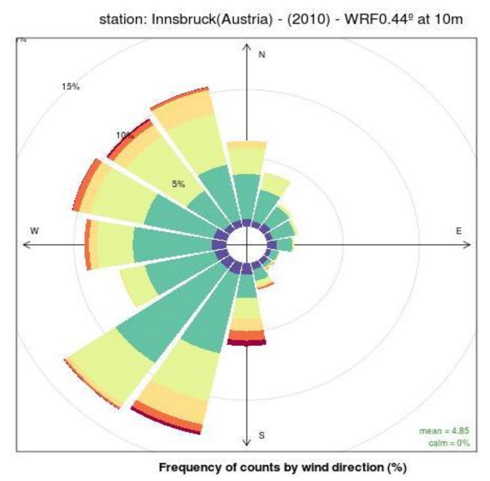


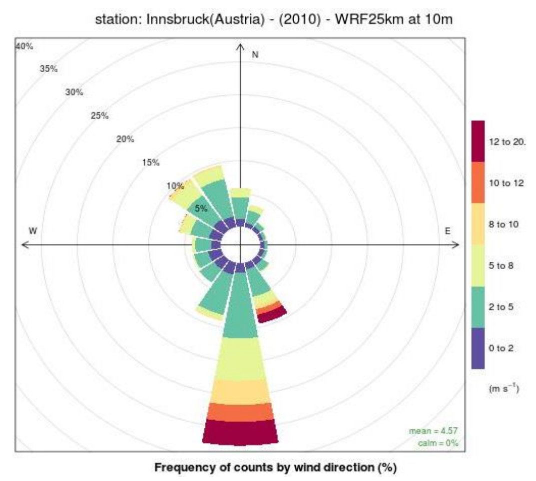




Mountain regions Metar stations







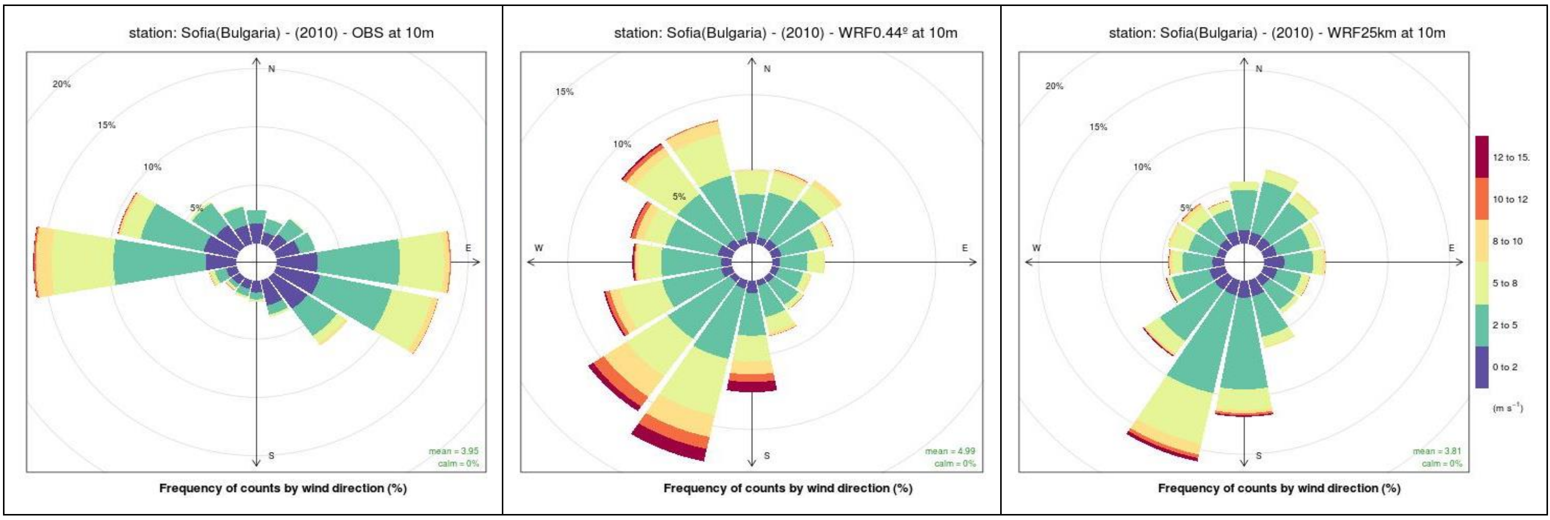
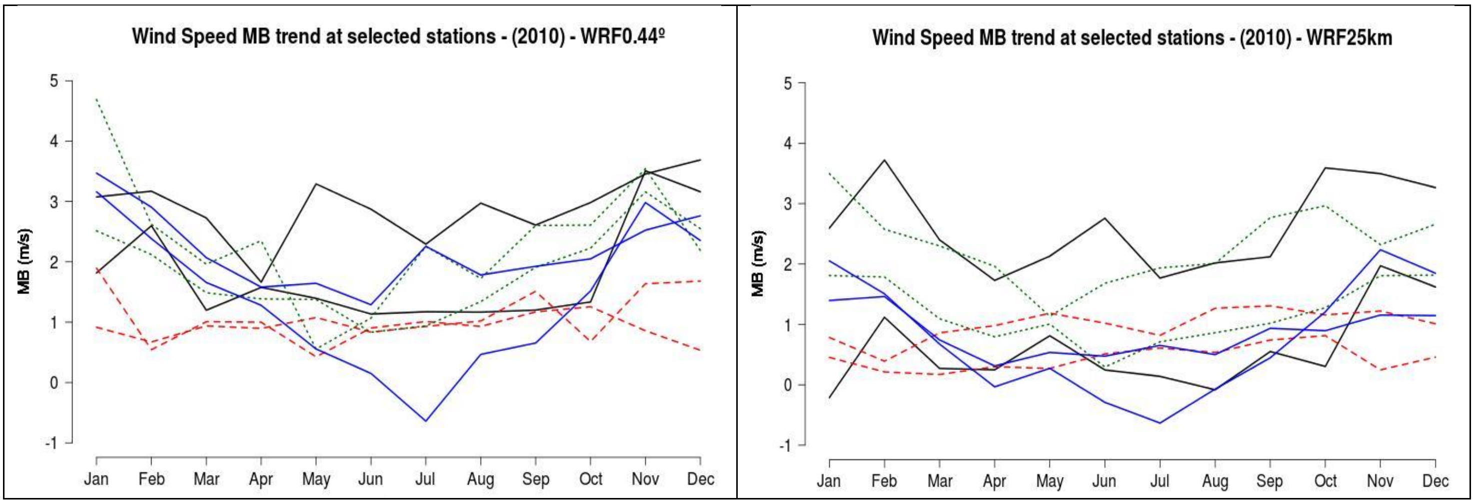


Figure 20. Wind roses series for selected stations over four different zones (from left to right: METAR observations, WRF0.44º and WRF25km)

The **Figure 21** and **Figure 22** represent the annual trend of the wind speed and wind direction statistic parameters, for both resolutions, for the selected stations:

- *black line* for mountain regions stations
- *blue line* for Mediterranean coasts stations
- *red dotted line* for flat continental stations
- *green dotted line* for Atlantic coasts stations



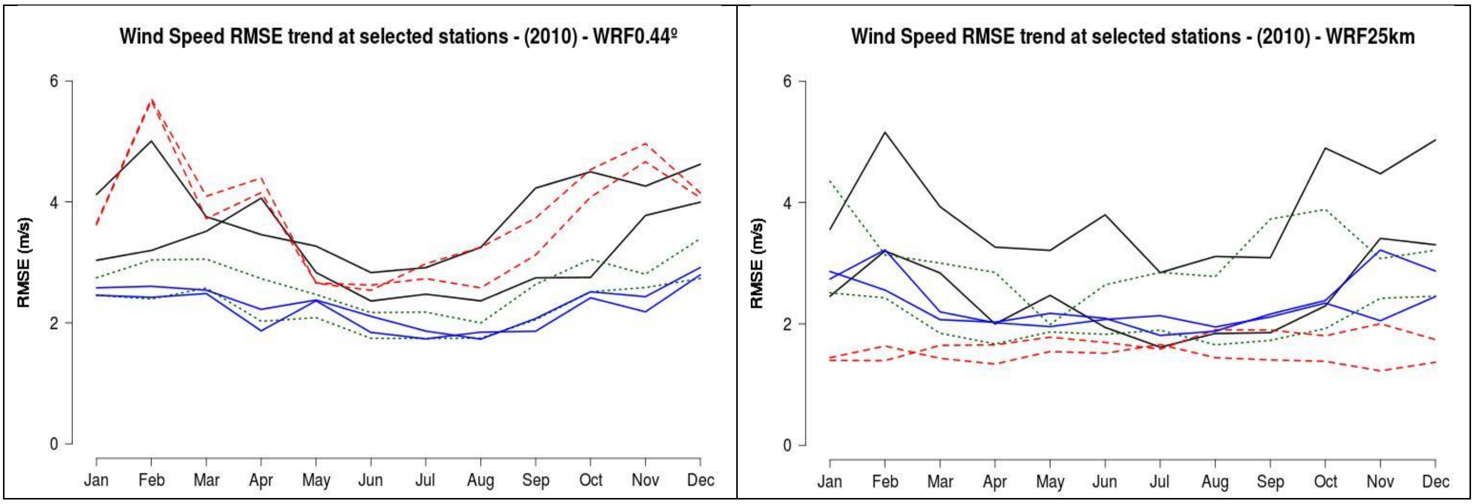
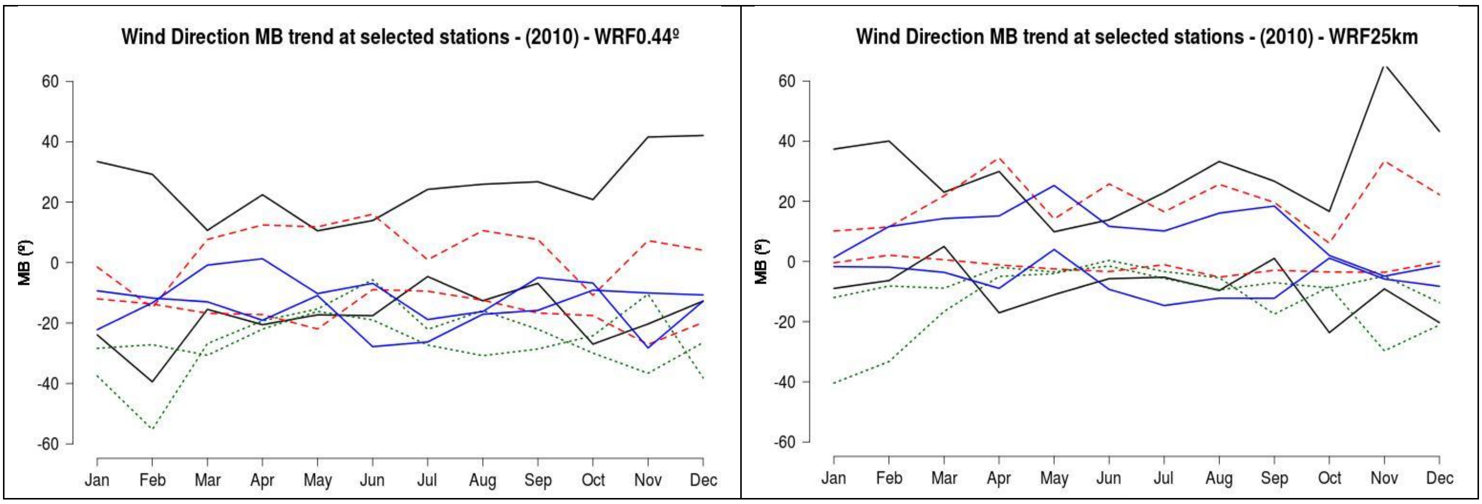


Figure 21. Temporal distribution of the wind speed statistical parameters for the 8 selected stations (1st row: MB and 2nd row: RMSE)

- The improvement of resolution from 0.44º to 25km reduces the overestimation mainly in the Mediterranean and Atlantic stations although the latter are both more overestimated than the Mediterranean ones. Only in one mountain stations shows a significant positive MB decrement (Sofia).
- The increment of horizontal resolution helps also to reduce the error in all stations but mainly in both flat and Mediterranean ones. The Atlantic stations just show a moderate decrement of error and positive bias although the worst model performance is over the Bergen station (Norway).
- The Innsbruck station analysis does not report an improvement with the resolution as it happens for the Sofia station. This is probably due to the local topography condition such as the wideness of valleys where both cities lie.



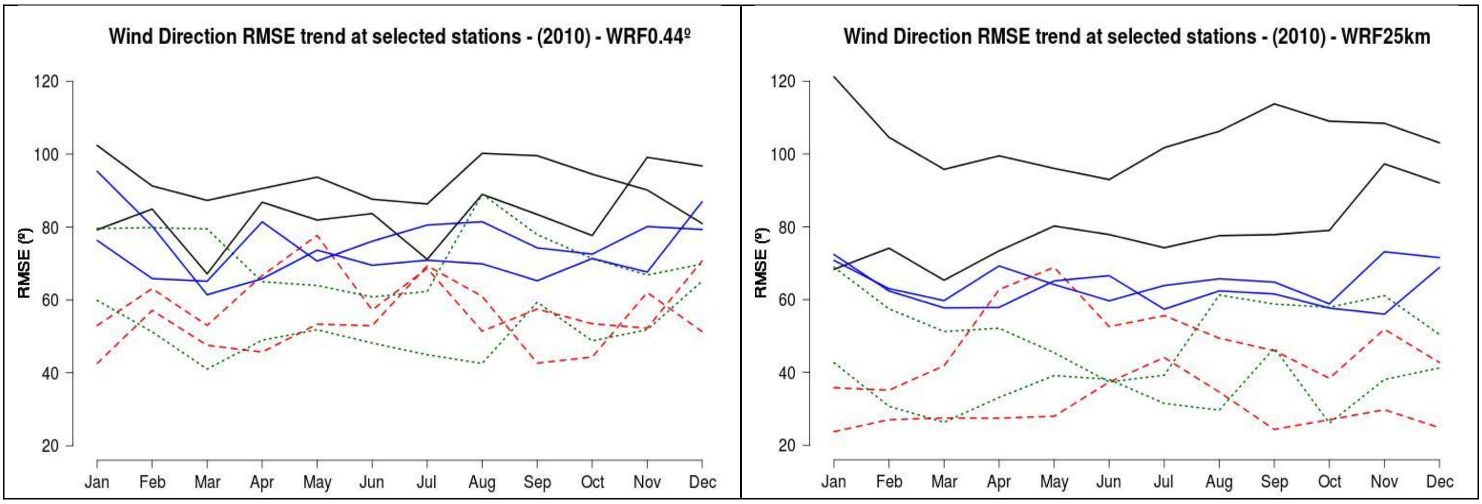


Figure 22. Temporal distribution of the wind direction statistical parameters for the 8 selected stations (1st row: MB and 2nd row: RMSE)

- The model tends to reproduce wind vectors from the left of the observations stations (anti-clockwise orientation) mainly over the western and central Europe therefore the MB is negative, while this becomes positive moving eastward. The finest WRF resolution reproduces a less negative MB over western and central Europe.
- The selected stations reproduce this behavior as the Atlantic stations have negative MB, while the flat stations have MB tending to 0 or beyond (-1.74º on average for Hamburg and 20.12º on average for Krivyy).
- The RMSE is reduced with the horizontal resolution increment for all the analyzed stations, mainly for the Atlantic and flat regions stations, with the exception of the mountain ones where it remains the same in Sofia's station event to get worse in the case of Innsbruck's one.

4. Conclusions

The meteorological comparison activity starts from two simulations of the year 2010 over a European domain performed with the WRFv3.3.1 model at 25km and 0.44º of resolution. The outputs data from both simulations have been compared against 371 observations stations of the METAR network scattered over Europe. These observations were used in order to produce temporal data series plots and statistics parameters and following, to assess the model performance at two different spatial resolutions.

About the temperature evaluation at 2m, the model tends to underestimate this variable over complex topography areas (Spain, north of Italy and Balkans countries) and to slightly overestimate in the rest of the domain (Continental and northern Europe) that is mainly flat (1K/3K). The tendency of underestimate is more remarkable in the WRF0.44º simulation and therefore more visible in the southern Europe (-3K/-4K). The WRF25km significantly reduces the underestimation presented in WRF0.44º, mainly during summertime whereas the error has been reduced significantly mainly from April to July.

The same spatial pattern is true also for the wind speed since both resolutions show less correlation over the south-eastern part of the domain (Italy, Balkans countries and eastern Mediterranean Sea) with worse performance showed by WRF0.44º. Over the same area, both results show a moderate overestimation (4 - 5 m/s) that tend to decrease over the central and northern Europe (1 – 2 m/s). The zones with the highest error are over the countries rising on the Norwegian Sea and over the eastern Mediterranean basin. Increasing the horizontal resolution allows a better adjustment of the sea/land interfaces, the orography and the mesoscale circulations, leading to improve the simulated winds. In fact, during the year, the highest resolution reduces the error primarily in wintertime and therefore the lowest MB values from both resolutions occur during the same period.

The analysis of wind direction shows a clear inclination of the model in simulating wind direction vectors at left of the monitoring stations (anti-clock wise orientation) over the Atlantic coasts up to central Europe, while the opposite orientations is true from central Europe towards eastern Europe countries. This negative bias is more visible during the cold months of the year, while it tends to zero (and go beyond for WRF25km resolution) during spring and summer time.

The evaluation of the WRFv3.3.1 has allowed understanding that it works better over central and north Europe as well as in some Atlantic areas, where the flat and smooth topography is predominant. The Mediterranean and Balkans countries with complex terrains are the areas where relevant discrepancies occur. On the other hand, the analysis of the model skills in function of the altitude has showed just a weak linear relation between altitude and quality of model output. This analysis has highlighted good model skill at both resolutions, but as it was expected, the simulation at 25km showed the best performance.

5. Acknowledgment

I want to express special gratitude to my colleague Lluis Vendrell for his fundamental helps in setting up and developing this work.